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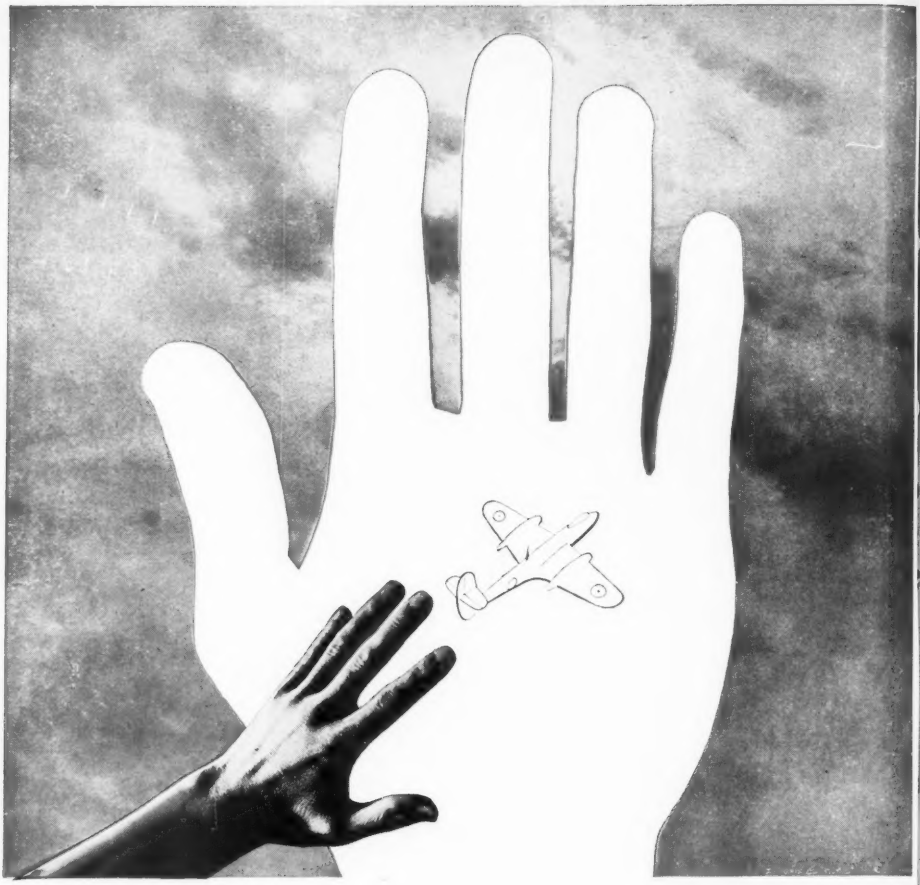

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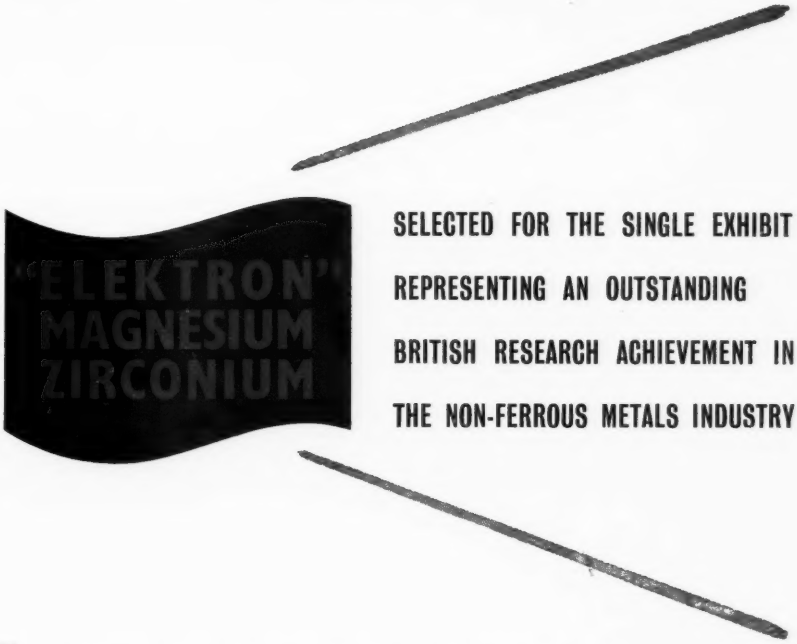

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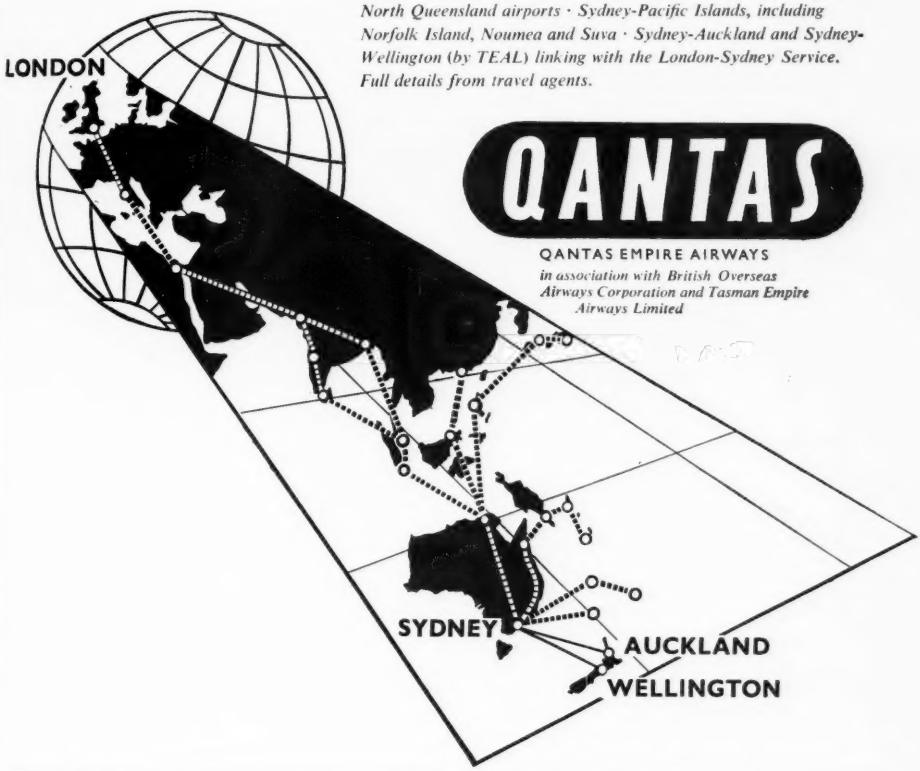

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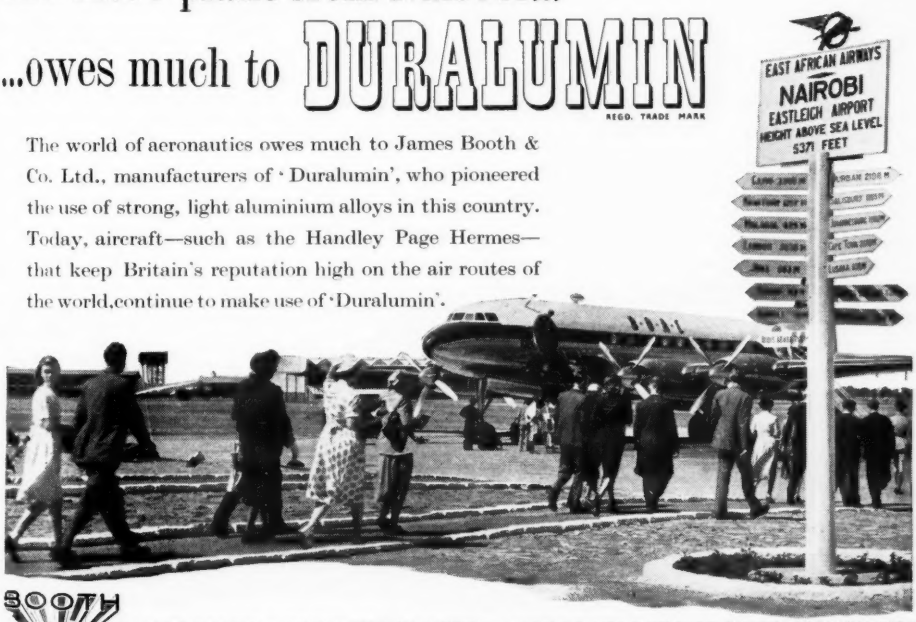

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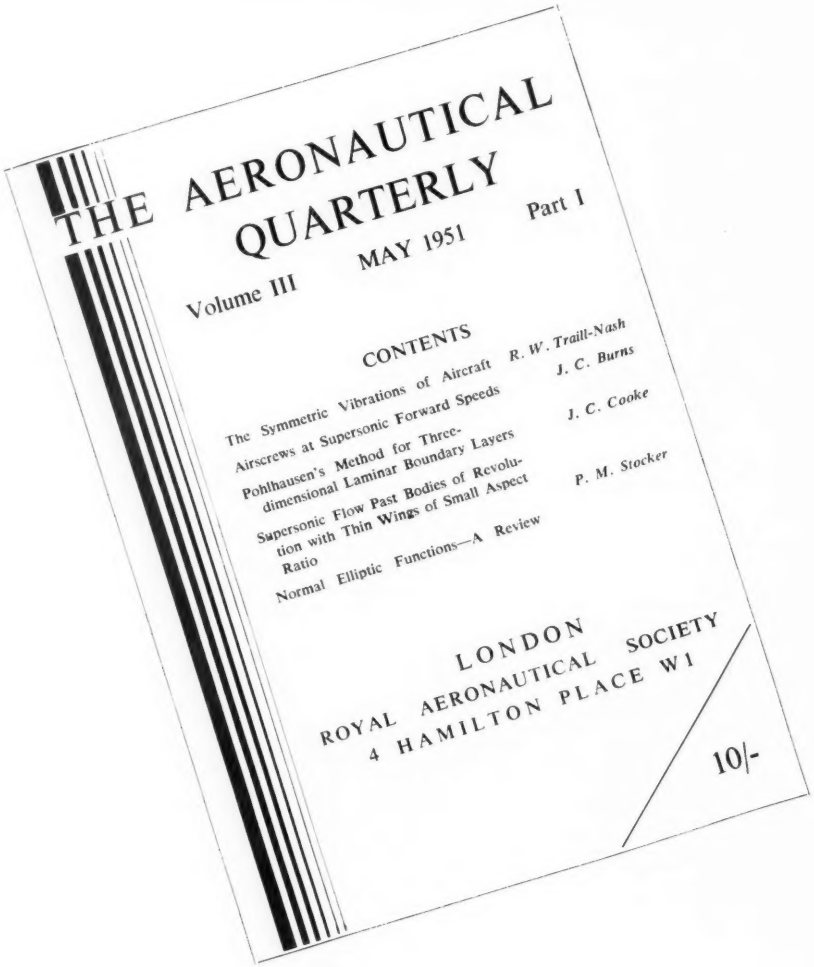
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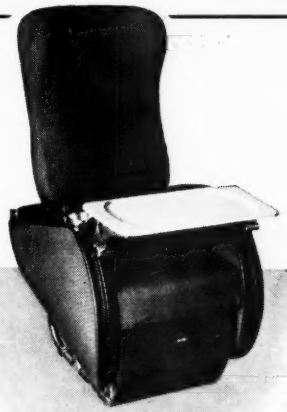

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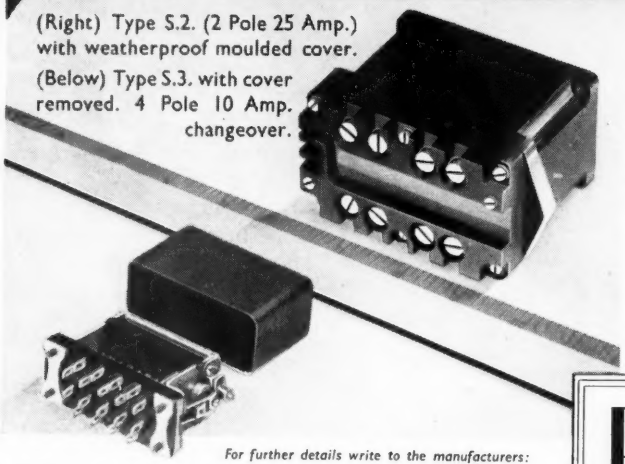

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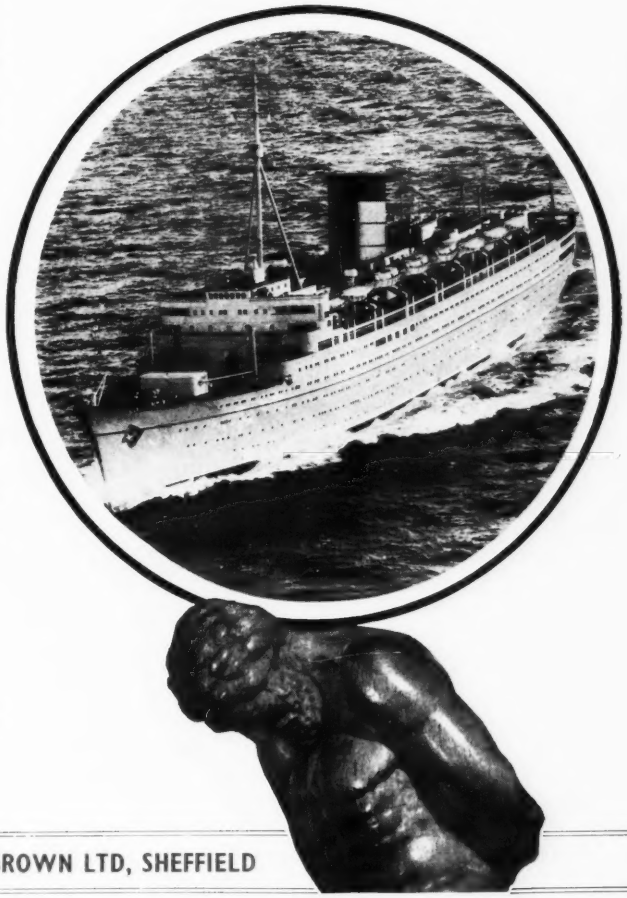

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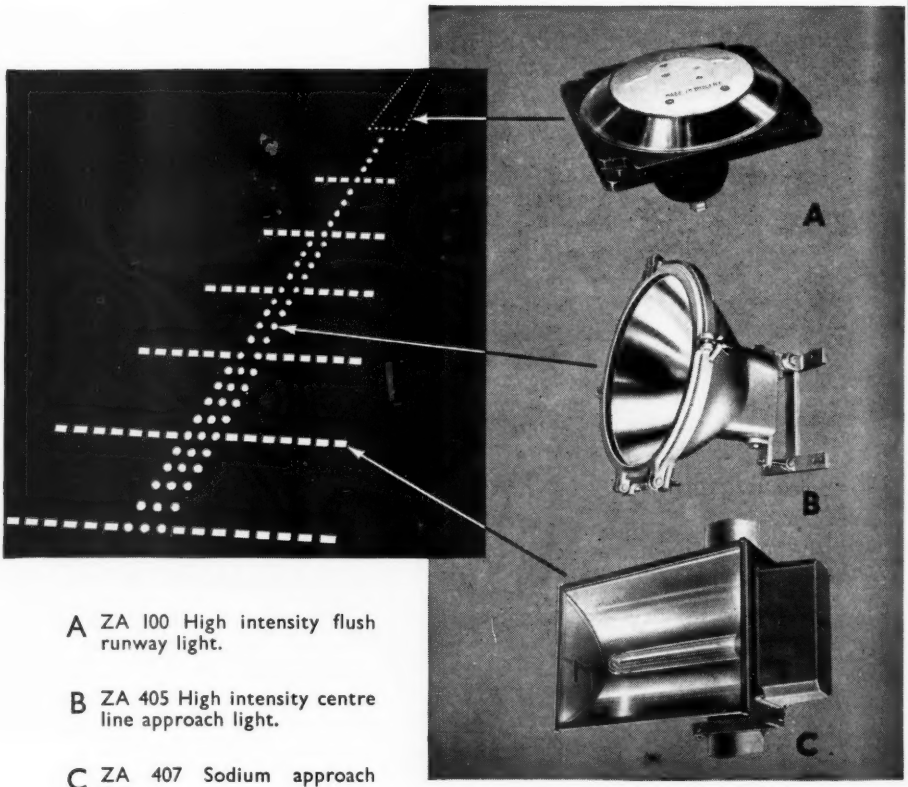

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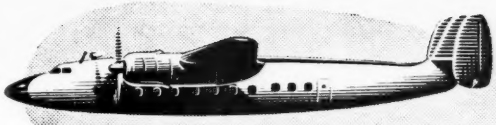

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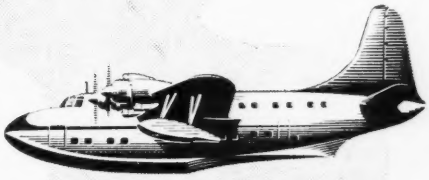

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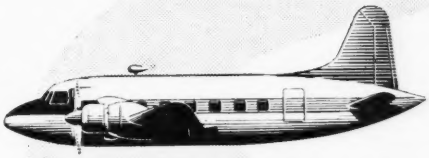

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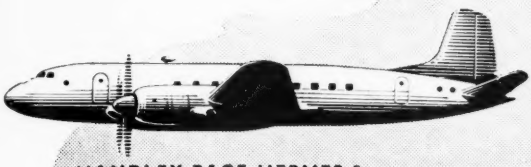

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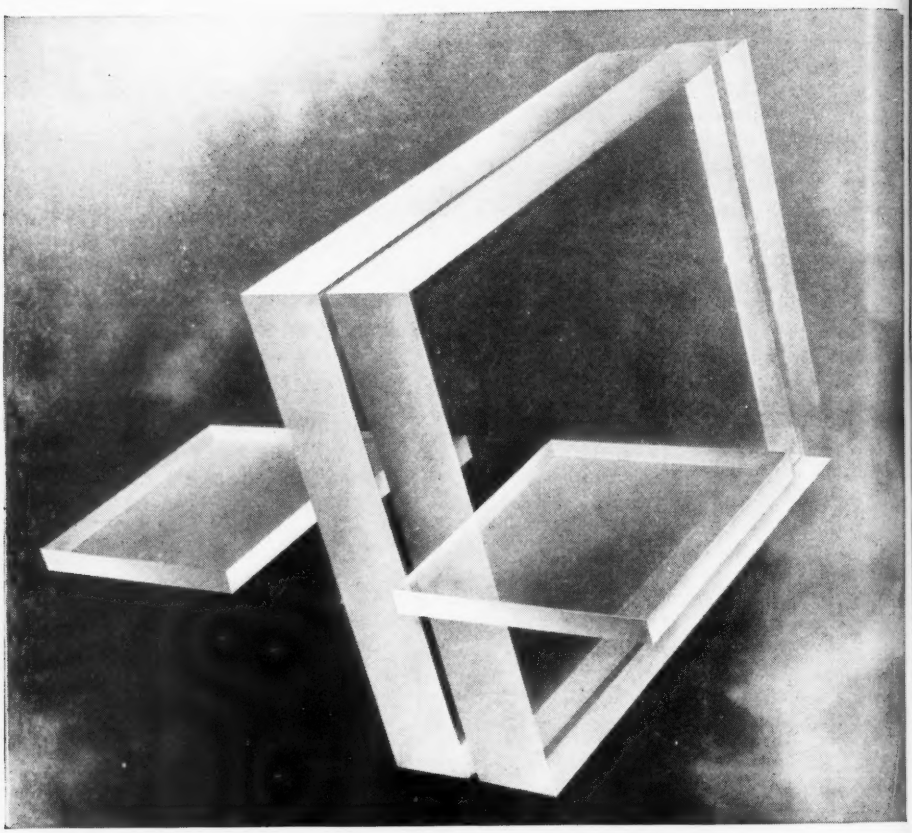

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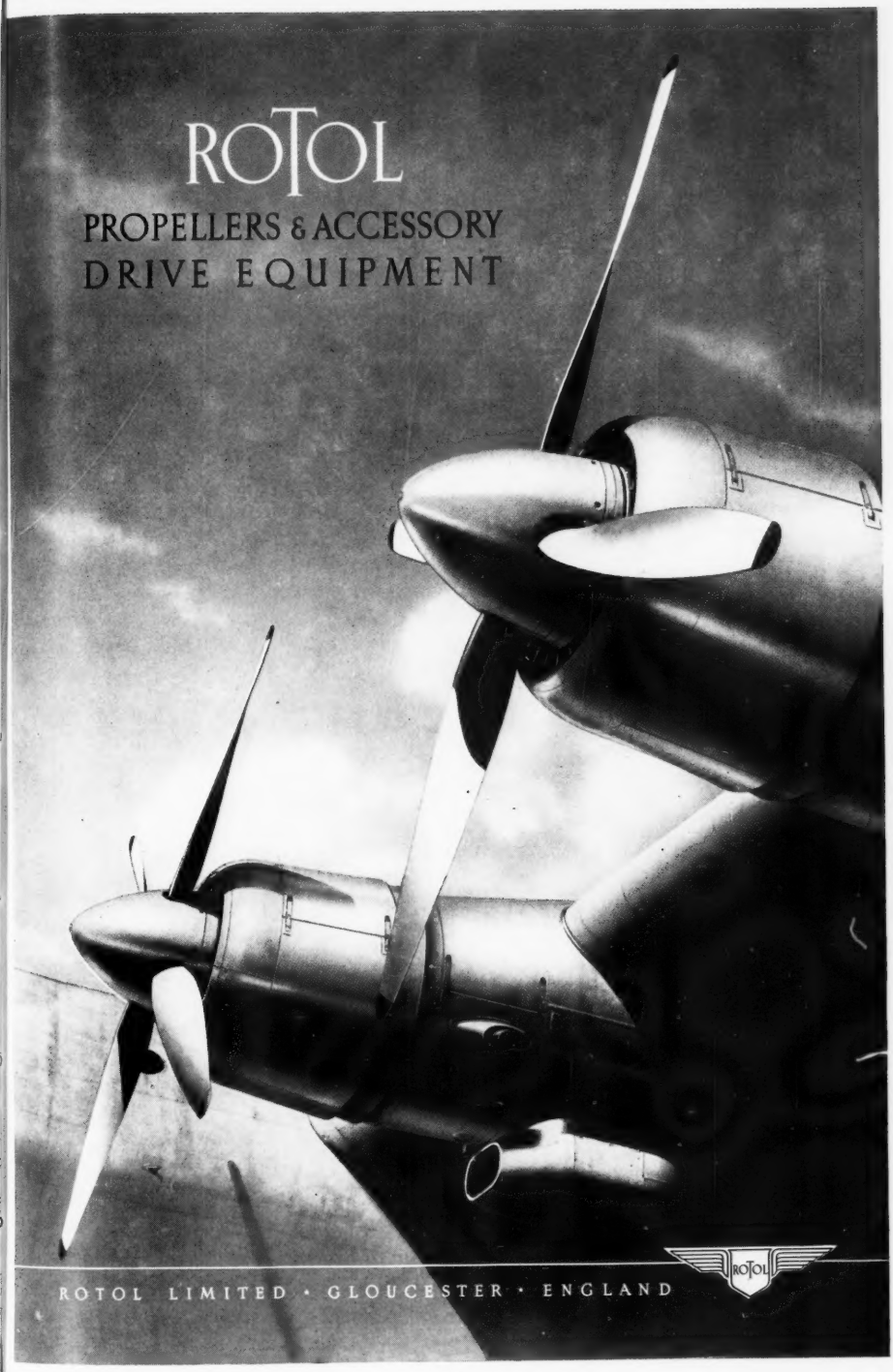
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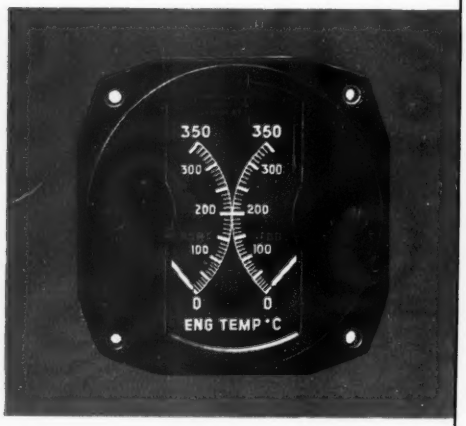

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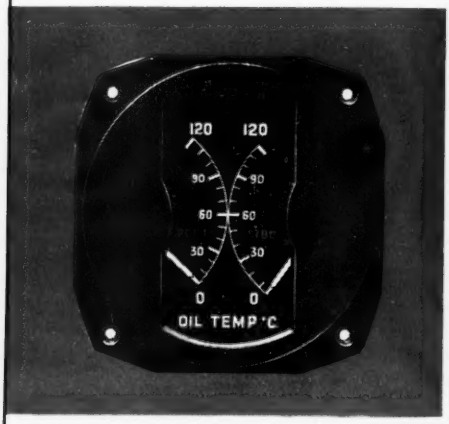

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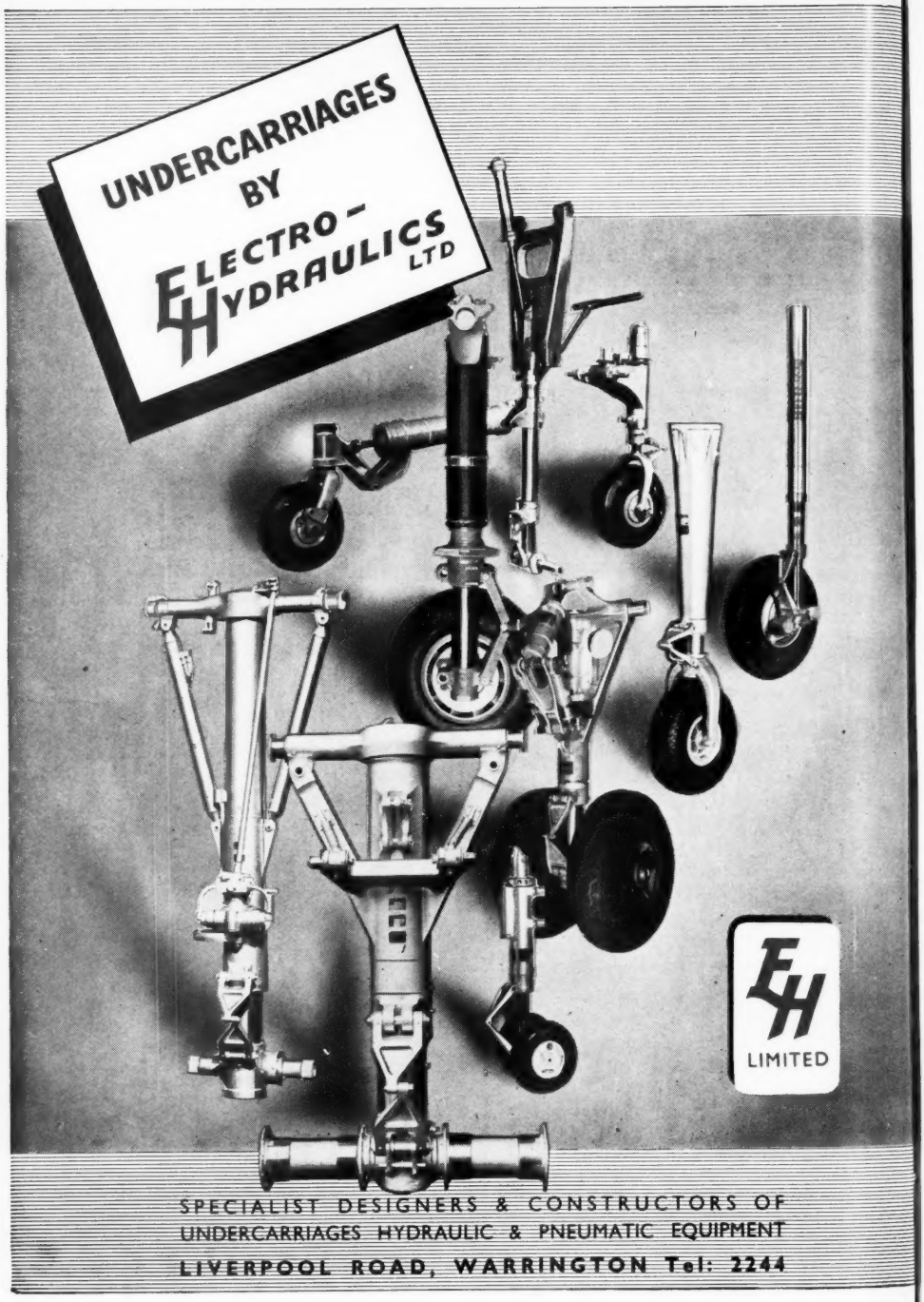
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Awarded for work leading to advance in aeronautics.

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Awarded for outstanding practical achievement leading to advancement in aeronautics.

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Awarded for practical achievement leading to advancement in aeronautics.

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Awarded annually, at the discretion of the Council, to the designer or inventor of any apparatus tending towards safety in flying.

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Awarded annually, at the discretion of the Council, for the most valuable paper read during the previous session.

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Awarded annually, at the discretion of the Council, for the most valuable contribution read before, or received by, the Society on any subject allied to aeronautics, *e.g.* structures, meteorology, metrology, etc.

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The Council offer an annual prize of twenty guineas for the best paper read before the Branches during the previous lecture session. The prize is open to any member of the Society or of any Branch.

SOME ASPECTS OF FLIGHT RESEARCH

by

HANDEL DAVIES, M.Sc., F.R.Ae.S., A.F.I.Ae.S.

The 817th Lecture to be given before the Royal Aeronautical Society was read under the auspices of the Coventry Branch on 15th February 1951, at the Sibree Hall, by Mr. Handel Davies, M.Sc., F.R.Ae.S., A.F.I.Ae.S., on "Some Aspects of Flight Research."

The Lecture was attended by the President of the Coventry Branch, Mr. H. M. Woodhams, C.B.E., F.R.Ae.S., the Chairman, Mr. W. J. Peters, the President of the Society, Major G. P. Bulman, C.B.E., F.R.Ae.S., and the Secretary, Captain J. L. Pritchard, C.B.E., Hon.F.R.Ae.S., and a number of members of the main Society and members of other Branches.

Mr. W. J. Peters, Chairman of the Coventry Branch, opened the meeting by welcoming the members of the main Society, particularly the President and Secretary.

He welcomed also members from the Manchester, Derby, Leicester, and Gloucester and Cheltenham Branches and one member from the Isle of Wight Branch. It was a great occasion for Coventry because it was the first Main Lecture of the Society to be given there and because it was a special celebration to mark the 25th anniversary of the founding of the Branch. Twenty-five years was a long time in the history of any organisation and he was glad to say that they still had with them some of the founder members who had done so much in the organisation of the Branch.

Major Bulman, President of the Society, said that normally Coventry would have been the first Branch of the Society at which a main Lecture was held because it was the prototype Branch, but the honour had been kept for the Silver Jubilee birthday of the Branch.

It was on 21st February 1926, he thought, that the Council agreed to the formation of the Coventry Branch and it was in March 1926 that the first lecture was given, by Mr. W. H. Farren on the Autogyro. The first President of the Branch was Mr. J. D. Siddeley, now Lord Kenilworth, with Major F. M. Green as Chairman and Mr. Meadows as Secretary. Major Shilson succeeded Mr. Meadows, and served for many years with them and on the Branches Committee of the Society. Today, they had as their President Mr. H. M. Woodhams and as their Secretary Mr. C. T. Sculthorpe. To them he expressed the Council's thanks for the work they did. It was on them and on the Committee that the prosperity and welfare of the Branch depended.

He brought to them the Society's warmest congratulations on their birthday and also a message from the Chester Branch, the youngest member of the family, which he had started off the week before; they asked him to convey: "To the oldest member of the family, felicitations and good wishes."

He now had much pleasure in introducing the Lecturer, Mr. Handel Davies, Head of the Flight Research Section of the Aerodynamics Department of the Royal Aircraft Establishment.

INTRODUCTION

Aeronautics has advanced a long way since that December day in 1903 when Wilbur and Orville Wright successfully completed the first flight test ever to be made on a powered aircraft. Since then much has been learnt about the science of aeronautics and great developments have taken place in the methods and techniques of aeronautical research. Wind tunnels have been built capable of testing models at very high speeds and at high Reynolds numbers, and many other powerful research techniques have been developed to assist in the design of aircraft. The behaviour of the aircraft itself in flight

remains the final test, however, and there are still many problems which can be investigated adequately only in flight with a piloted aircraft.

In this lecture it is proposed to illustrate the contribution which flight research can make towards the advancement of knowledge of aeronautics by discussing some of the more important aspects of this work.

The field covered by the title "Flight Research" is a wide one, and it will not be possible to present anything like a comprehensive survey in a lecture of this nature. An attempt will be made to give as representative a picture as possible by discussing some typical examples of developments in flight research under three main headings:—

1 Work concerned directly with reducing the drag of aircraft.
2 Research on stability and control problems.
3 General aerodynamic research.

In order to cover as wide a field as possible the emphasis will be on the results obtained in this work rather than on detailed descriptions of the experimental techniques involved.

1. FLIGHT RESEARCH ON THE DRAG OF AIRCRAFT

One of the main contributions which flight research can make towards improving the performance of aircraft is to measure the speed and the drag of aircraft in flight, to analyse the sources of this drag and to explore methods of reducing it. Perhaps the best example of this aspect of flight research is provided by the work done at the Royal Aircraft Establishment in recent years to investigate boundary layer effects on aircraft and in particular, to determine the conditions under which extensive areas of laminar flow can be achieved in flight. This work will be discussed in some detail.

1.1. Boundary layer research in flight

There is no need to describe in detail the tremendous improvements in performance which can be achieved if the boundary layer can be kept laminar over a substantial part of the surfaces of the aircraft. These potential gains were fully discussed by Mr. E. J. Richards[1]. It will be sufficient to point out that the drag of an all-wing aircraft is approximately halved if the transition from laminar to turbulent boundary layer moves back from the leading edge to about 50 per cent. of the chord.

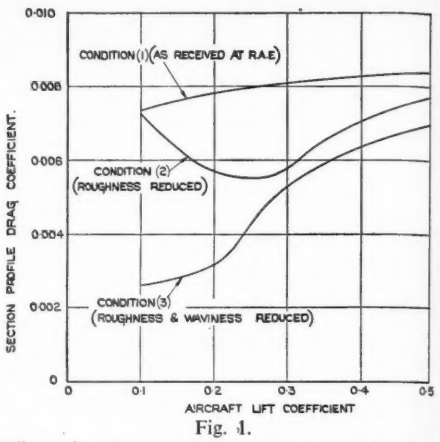


Fig. 1.
Effect of surface condition on section profile drag (King Cobra).

The first step in achieving such a far back transition is to design the wing so that the pressure gradient remains negative as far back as possible and over a reasonable speed range. There is no difficulty in doing this and many aircraft have now been built with wings designed to retain a favourable gradient over more than half the wing chord for a wide range of life coefficient. If the complication of boundary layer suction is accepted, a favourable pressure gradient can be retained over practically the whole wing surface without ruining the wing characteristics from other points of view.

Unfortunately the maintenance of a favourable pressure gradient is very far from providing a guarantee of laminar flow, since an early transition can easily be caused even in a steep favourable gradient by small irregularities or excrescences on the wing surface. These irregularities may be placed in two categories:

(*i*) Irregularities inherent in the construction or finish of the wing, such as skin waviness, overlap in skin joints, or roughness in the surface finish.
(*ii*) Irregularities arising from contamination of the wing surface by dirt, insects, and so on.

It is obvious that flight research must play a very important part in investigating these factors. The work which has been done in this connection during the past few years

TABLE I

Condition	C_{D_0} *at* $C_L=0.2$	*Estimated transition*
(1) As received at R.A.E.	0.008	Near L.E.
(2) Slight surface improvements	0.005	0.354*c*
(3) Waviness reduced (*see* Figs. 3 and 4)	0.003	0.65*c*

will be discussed in some detail, and an attempt will be made to determine the standards of construction needed and the importance of the contamination problem.

1.1.1. *Effect of surface waviness and finish*

The effect of surface irregularities on the transition position depends on the Reynolds number at transition and on the magnitude of the pressure gradient. The tests which have been made in flight have not been sufficiently systematic or comprehensive to separate out these effects completely, but enough has been done to give a reasonable indication of the standards which must be aimed at, and to provide some check on the systematic work of Fage[2] and others.

In most of these flight tests the extent of the laminar boundary layer has been determined by one of the chemical methods developed mainly by W. E. Gray[20] with the assistance of members of the Chemistry Department at the R.A.E. The first of these methods to be used in flight depended upon flying the aircraft through a trail of gas which reacted chemically with a thin liquid coating applied to the wing surface. The reaction in the region of turbulent flow was much more rapid than in the laminar boundary layer, and the discolouration produced gave a clear indication of the transition. The liquid used to coat the wing was a solution of one gm. of starch, 3 gm. of potassium iodide and ½ gm. of sodium thiosulphate in 100 cc. of water, and the aircraft was flown through a trail of chlorine gas laid by another aircraft, which also laid a smoke trail to indicate the position of the chlorine.

More recently two methods have been developed which dispense with the necessity for laying a trail of gas. One of these methods relies on the oxidising by the air flow of a solution of potassium iodide, starch, and sodium thiosulphate sprayed in a thin coating on the wing surface. The second method depends on evaporation or sublimation of a thin coating of a volatile chemical sprayed on the wing. Coatings of naphthalene, camphor, and fluorene have been used successfully for this purpose. The main disadvantage of these methods is that it is necessary either to protect the test section of the wing by some sort of jettisonable covering during taxi-ing, take-off and climb, or to fly under the test conditions for a much longer time than the time taken to reach the required altitude, with the constituents of the chemical coating adjusted to give the appropriate reaction time.

The extent of the laminar boundary layer has also been determined indirectly in flight by measuring the section profile drag coefficient, using a pitot comb mounted behind the test section, and the results in some cases compared with the chemical methods.

The most comprehensive flight tests on these lines have been on a Bell P.63 (King Cobra)[3]. This aircraft has a 66-series wing section, with a maximum thickness-chord ratio of 16 per cent. located at 45 per cent. of the chord, giving a peak suction at about 0.60*c* at $C_L=0$. Thus laminar flow should be possible over at least half the wing surface.

In the form in which the aircraft was originally received at the R.A.E. it became clear that the transition was very close to the leading edge. Measurements of section profile drag coefficient by Smith and Higton[3], using a pitot comb, gave a value of 0.008, which was equal to the estimated value of C_{D_0} for leading edge transition. Removal of small local surface defects, such as grit embedded in the paint, immediately reduced this drag coefficient to 0.005, at any rate for lift coefficients near 0.2, and this implied an average transition in the neighbourhood of 0.35*c*. Eventually, by improving the standard of surface waviness until the maximum variation on a waviness gauge with a 2-inch base was less than five thousandths of an inch, the profile drag coefficient was brought down to about 0.003 at $C_L=0.2$. This implied a transition at about 0.65*c*.

These results are shown in detail in Figs. 1 and 2, and summarised in Table I. The surface waviness records corresponding to the two main conditions tested are given in Figs. 3 and 4.

Experiments on a similar aircraft by W. E. Gray, using the chlorine method to observe the transition, broadly confirmed these conclusions, but were much more instructive in indicating the precise sources of early transition. These experiments showed in particular

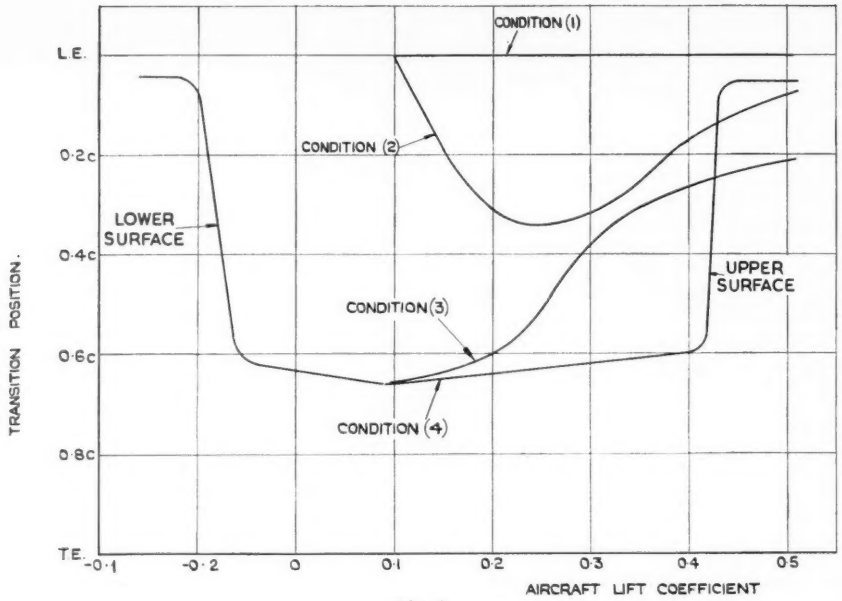


Fig. 2.
Effect of surface condition on transition (King Cobra).

the importance of a ridge at a skin joint, a 0.006-inch step down causing almost immediate transition. Eventually the surface condition was improved to such an extent that the remaining surface waviness represented variations of less than two thousandths of an inch measured on an Ames gauge with two-inch base, and irregularities at skin joints and rivets had been removed entirely (*see* Fig. 5, Condition (4)). Chemical observations of transition in this condition (extending incidentally to zero and slightly negative C_L's) showed that this final improvement had very little effect on the transition position at lift coefficients near 0.2, but it did widen the range of C_L over which the transition can be kept back at 0.65*c*, to a maximum C_L of about 0.4, when the transition jumped abruptly forward (*see* Figs. 2 and 6, Condition (4)).

This probably represents one of the best surface conditions ever achieved on an aircraft wing, and shows that at any rate at the Reynolds numbers of these tests (10-17 million, based on wing chord) laminar flow can be retained so long as the gradient does not become definitely unfavourable. In fact, in this case the transition was often behind the peak suction and also survived a small region of positive pressure gradient near the nose. This is illustrated in Fig. 7 showing pressure distributions on this wing measured in the R.A.E. No. 2 11½ ft. tunnel. It will be seen that at low lift coefficients, laminar flow was retained to at least 0.05*c* behind the pressure peak, while at lift coefficients approaching 0.4 the far back transition is retained in spite of the fact that the magnitude of the favourable gradient is everywhere small, and in spite of the unfavourable region near the nose.

These results also illustrate the dependence of waviness requirements on pressure gradient. The forward movement of the transition in Condition (3) at lift coefficients above 0.2 undoubtedly was due to the reduction in favourable gradient with increasing C_L.

Similar tests have been made on a Hurricane[4], fitted with special low drag wings manufactured by Armstrong Whitworth Ltd. This wing was designed to give a peak suction at about 50 per cent. chord, and had a thickness/chord ratio varying from 17.9 per cent. at the root to 14.8 per cent. at the tip. The wing had a fairly thick skin (18 gauge) stiffened by spanwise stringers three inches apart, the top and bottom surfaces

GAUGE READING X 1000 (INCHES)
GAUGE READING X 1000 (INCHES)

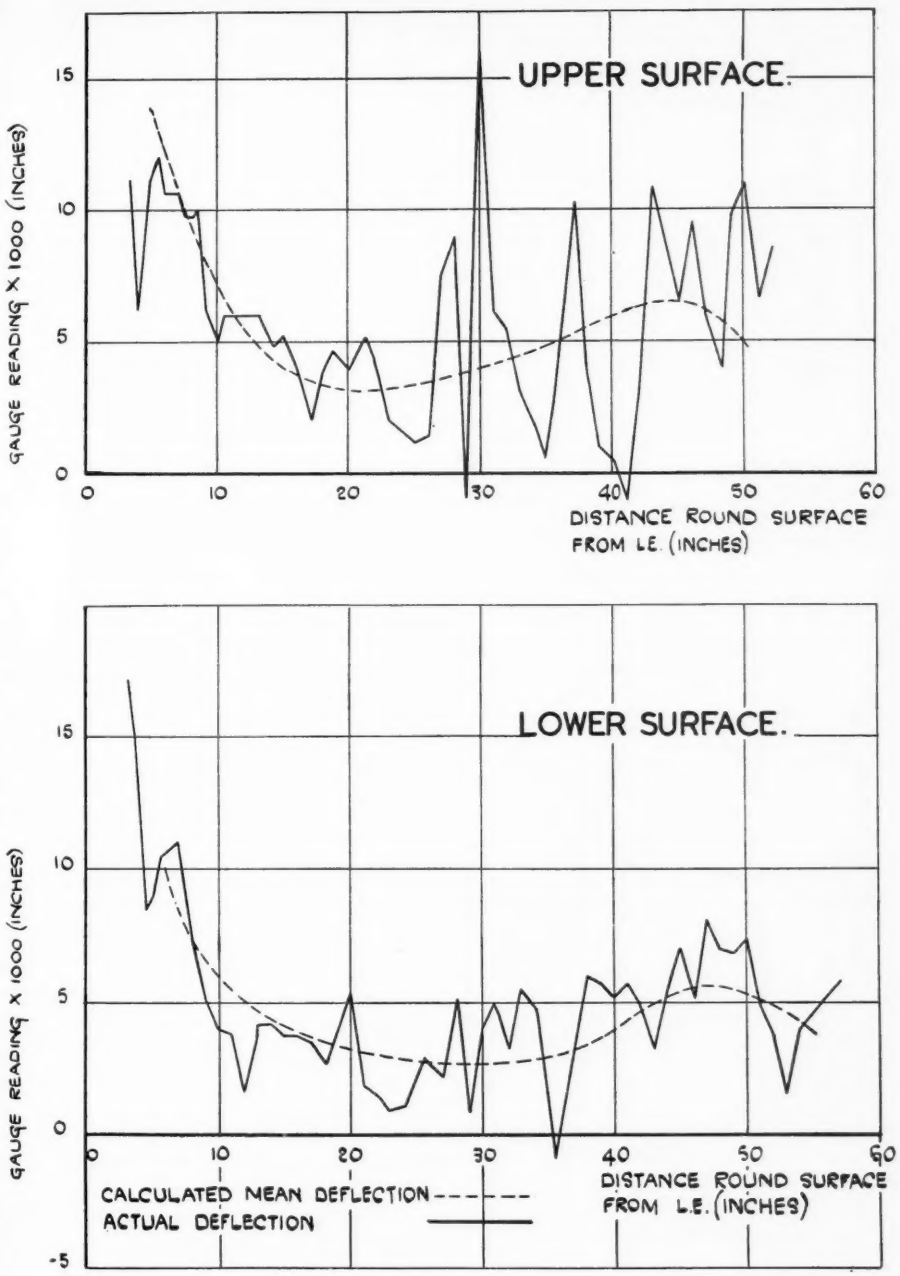


Fig. 3.
Surface waviness of King Cobra wing in condition (1) (as received at R.A.E.).

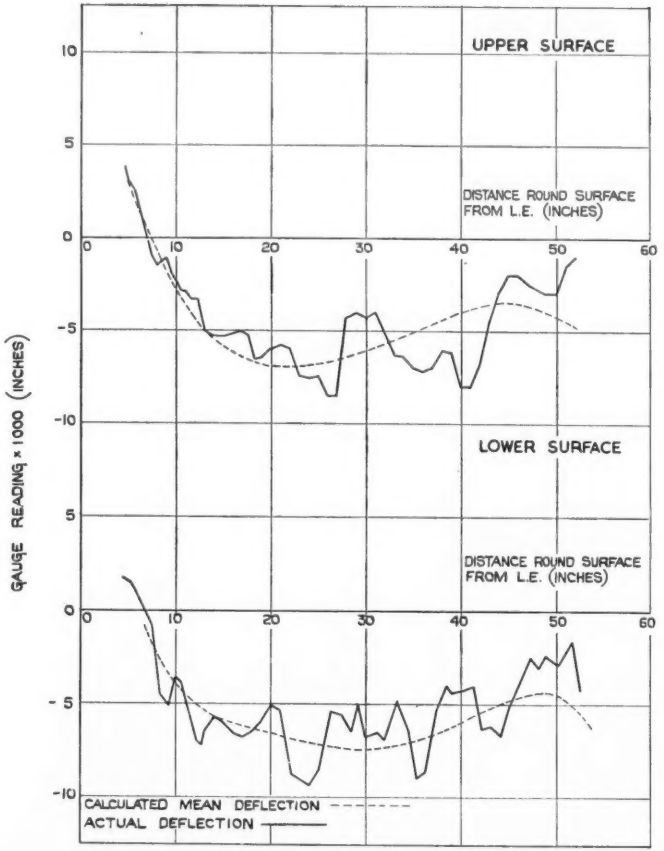


Fig. 4.
Surface waviness of King Cobra wing in condition (3) (roughness and waviness reduced).

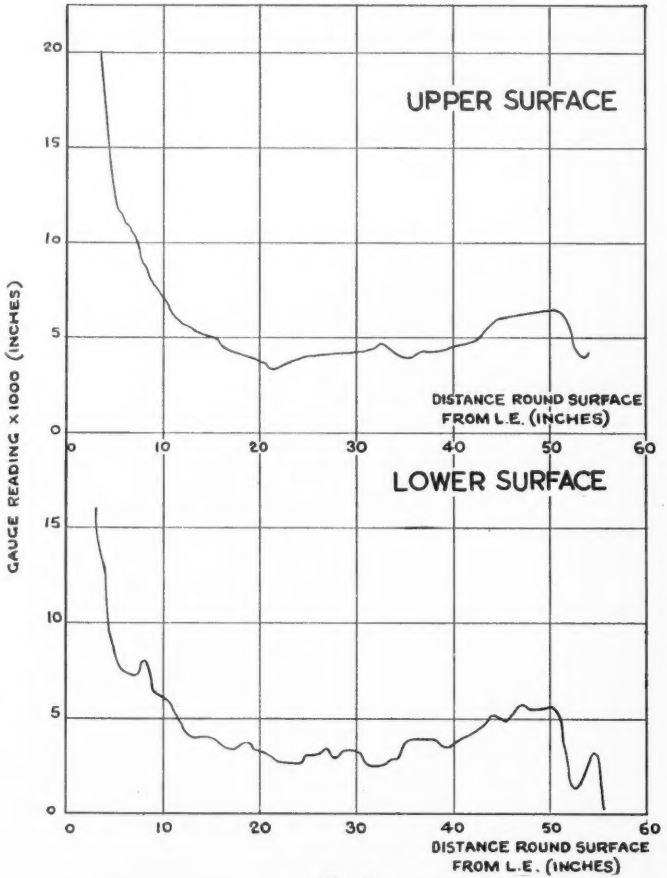

UPPER SURFACE
DISTANCE ROUND SURFACE FROM L.E. (INCHES)
LOWER SURFACE
DISTANCE ROUND SURFACE FROM L.E. (INCHES)
GAUGE READING × 1000 (INCHES)

Fig. 5.
Surface waviness of King Cobra wing in condition (4).

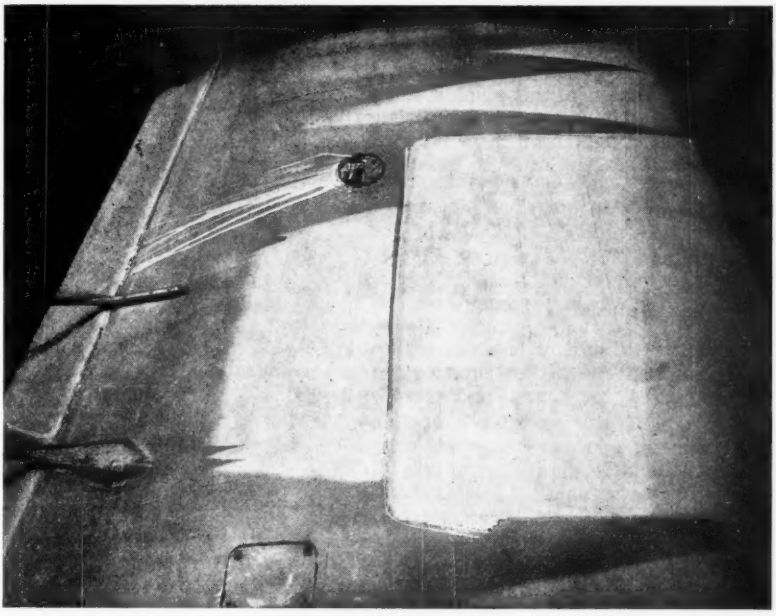


Fig. 5.
Surface waviness of King Cobra wing in condition (4).

Fig. 6.
Transition at 65 per cent. chord on upper surface of King Cobra wing in condition (4).
($C_L = 0.14$, $R = 17 \times 10^6$, air speed indicator reading = 300 m.p.h.)

Fig. 4.
Surface waviness of King Cobra wing in condition (3) (roughness and waviness reduced).

being connected by ribs 15 inches apart. A very good surface was thereby achieved, and Figs. 8 and 9 show the results obtained for the original condition and after some reduction in surface condition had been achieved by rubbing down.

It will be seen that transition at about 50 per cent. chord was achieved even in the original condition (*i.e.* with waviness limits of the order of three thousandths of an inch) at lift coefficients near 0.2. The effect of reducing the waviness to a maximum of one or two thousandths widened the C_L range as on the King Cobra[3], the waviness requirements being more stringent as the favourable pressure gradient decreases with increasing C_L. It will be seen that reducing the waviness also had a favourable effect at lift coefficients below 0.2. This is due to the increasing Reynolds number in the flight tests at these low C_L's, which again has the effect of making the waviness requirements more difficult to meet.

These tests have shown that for Reynolds numbers of the order of 15 million, based on wing chord, it is necessary to reduce the waviness of the wing surface, as measured on a two-inch gauge, to something of the order of one thousandth of an inch, if the transition is to be kept right back to the pressure peaks, over the full C_L range for which the wing has been designed. This is in general agreement with the waviness standards suggested by Fage[2]. It represents a very severe demand on the manufacture and maintenance of wings, and few operational aircraft yet produced have come anywhere near to achieving this standard.

It is worth emphasising that a transition near the pressure peak can be achieved for a small C_L range, when the favourable pressure gradients are high, with appreciably lower standards of waviness, perhaps up to three or four thousandths, at these Reynolds numbers. This suggestion should not be allowed to discourage efforts to produce better surfaces, and is made, in fact, largely in order to counter the defeatism which exists in some quarters about the practicability of achieving even a moderate extent of laminar flow on a service aircraft. The truth is that the attainment of full extent of laminar flow, theoretically possible over the entire design range of C_L, is extremely difficult in practice,

especially at high Reynolds numbers; but it is not difficult to go quite a long way towards this ideal.

As a further illustration of this point, it is worth mentioning that a test made recently at the R.A.E. on a jet fighter which had not been specially treated, except for a very small amount of rubbing down near the leading edge, gave a transition of 30-40 per cent. of the chord over a large proportion of the wing surface, apart from a few wedges (*see* Fig. 10). In this case the skin joint was at the leading edge, and the waviness standard was extremely good for a production aircraft. On the other hand two other jet aircraft tested at the same time had a mean transition at about 0.10*c*, caused by poor rivets and skin joints.

Thus, although an enormous amount of effort is needed to achieve the full advantage theoretically possible over the design C_L range, a considerable gain can be achieved with very little trouble in construction and maintenance. How far even such a limited gain may be prejudiced by dirt and insect contamination will be discussed later.

1.1.2. *Boundary layer research at very high Reynolds number*

The work described so far has been concerned with Reynolds numbers up to about 17 million. It has been seen that as the Reynolds number increases, the standard of surface waviness needed to ensure transition in the neighbourhood of the pressure peak becomes more severe.

It is important therefore to investigate the conditions under which a far back transition can be achieved at the highest Reynolds numbers likely to be met in practice. The view has been put forward that there may be a definite upper limit to the Reynolds number at transition even for a perfect wing, the limit suggested being of the order of 16 million. W. E. Gray has drawn attention to existing experimental results which appear to contradict this suggestion, and it is important to try to obtain a further experimental check on this point. Flight tests, therefore, are being made at the R.A.E. on the Armstrong Whitworth 52, observing transition by the evaporation method as the wing surface is progressively improved. If laminar flow can

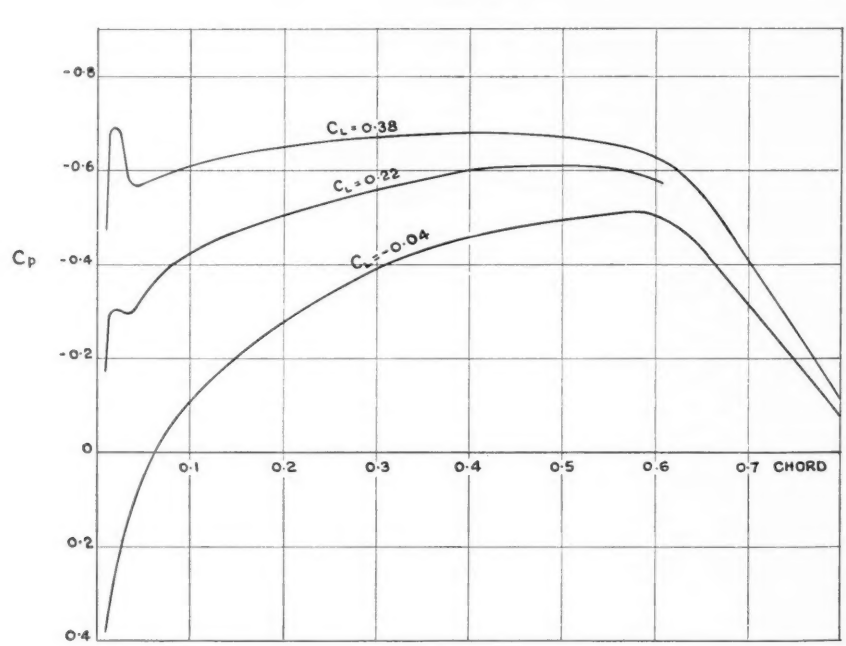


Fig. 7.
Pressure distributions on the upper surface of King Cobra wing in condition (4).

be maintained as far back as the pressure peaks on this wing, the Reynolds number at transition will be about 22 million, at the maximum speed. This is well above the suggested limit. The experiment will also serve to check the standard of surface finish and waviness needed to maintain laminar flow at higher Reynolds numbers than have been covered in any flight tests up to now.

1.1.3. *Boundary layer research at high Mach numbers*

The possibility of maintaining laminar flow at high Mach numbers has not as yet received much attention. The problem does not seem to be fundamentally altered even when the Mach number is high enough for there to be extensive regions of supersonic flow and shock waves present on the wing. A negative pressure gradient is still favourable to the maintenance of laminar flow, the only difference being that as the Mach number increases the region of favourable gradient in general becomes more extensive, and in fact extends as far as the shock wave.

It is clearly important to investigate whether the standard of surface finish and waviness needed to ensure laminar flow back to the pressure peak under these conditions is the same as at low Mach numbers. Some preliminary work has been done on this problem at the R.A.E., using a de Havilland Vampire. The results suggest that the surface standards needed to achieve a given amount of laminar flow are much the same as at lower Mach numbers, for the same Reynolds numbers, but more systematic flight work is needed on this subject.

1.1.4. *Contamination by insects*

In all that has been said so far it has been assumed that the wing has been thoroughly cleaned before take-off and that no contamination of the wing surface has subsequently taken place. Unfortunately serious contamination of the wing often does occur, particularly from insects, and this constitutes one of the most difficult practical problems in making use of laminar flow wings. Very minute insects or specks of dust are sufficient to initiate a wedge of turbulent flow and Fig. 11 illustrates the sort of thing which may happen.

The magnitude of the insect problem varies widely with geographical position, time of year, time of day, and weather conditions, and it will be worth quoting briefly

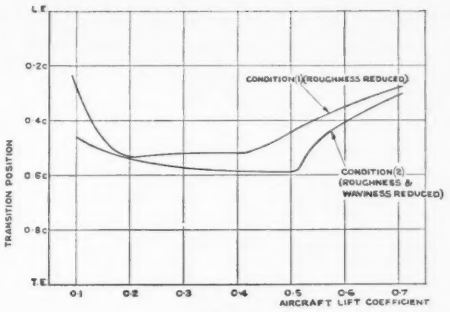


Fig. 8.
Effect of surface condition on transition position (Hurricane Z 3687).

the experience gained on this subject during flight tests at the R.A.E. and elsewhere, although little systematic information is available.

During the winter months the number of insects picked up during one take-off in the Farnborough area is usually very small, especially in the mornings. In recent flight tests on the A.W.52 at the R.A.E., for example, the number of insects picked up per flight never exceeded one per 10 ft. span, and in most morning flights no insect contamination occurred at all. Rainy conditions and high winds also seem to tend to reduce the insect population.

In warmer weather the number of insects increases and on the afternoon of a warm summer day there have been occasions when so many insects have been picked up that the effective transition is brought near the leading edge over most of the wing surface. Even in midsummer, however, the number of insects collected in an early morning take-off is usually small. Insect contamination also tends to become a more serious problem in warmer climates. During some systematic observations made in Louisiana in the U.S.A., for example, one insect was picked up per square foot of wing frontal area for every minute of a flight at 500 ft.

It seems then that the insect problem varies with geographical situation, time of year, time of day and weather conditions, from being relatively unimportant to being sufficiently serious virtually to prevent the maintenance of laminar flow over any appreciable proportion of the wing surface. Unfortunately, the mere possibility of a premature transition being caused by insects on some occasions is sufficient to prevent full

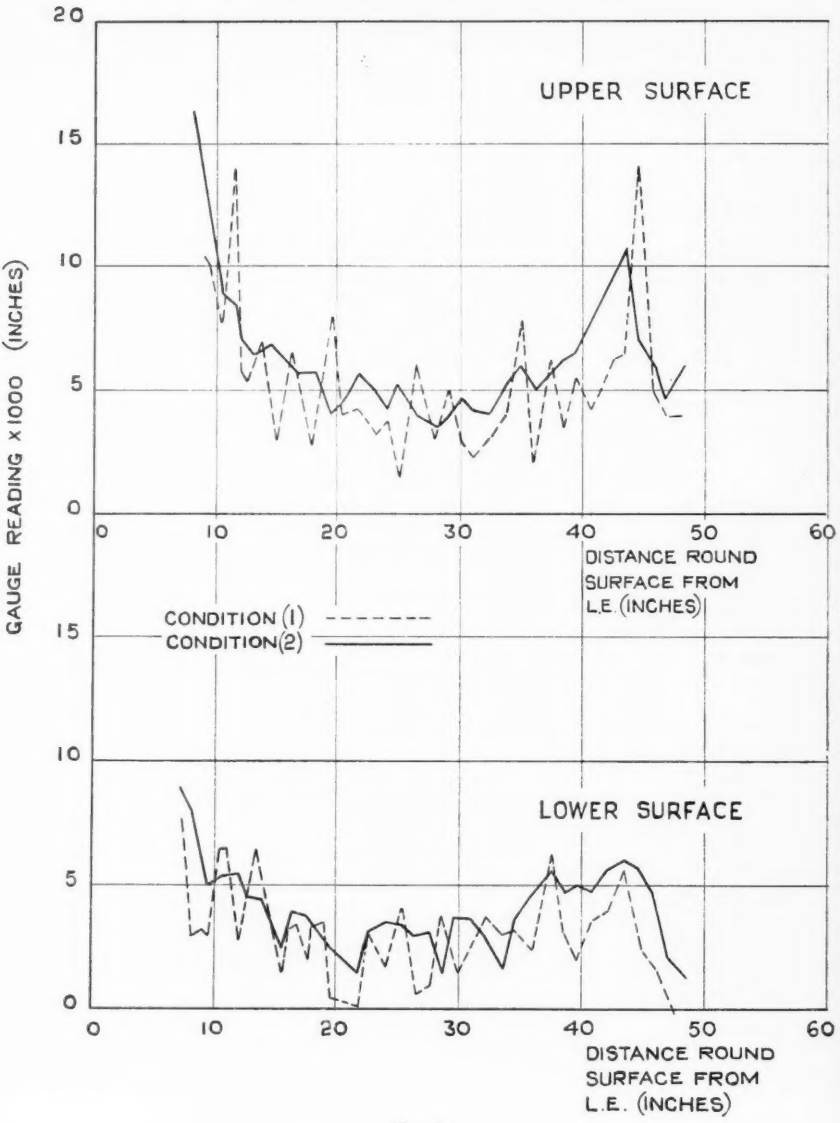


Fig. 9.
Surface waviness of Hurricane Z 3687 wing in conditions (1) and (2).

use being made of laminar flow wings in achieving long range. It should not, however, discourage efforts to achieve extensive areas of laminar flow as a means of attaining higher speeds under favourable conditions.

The area of wing which may be affected by insect contamination is not very large, extending perhaps from about 0.20*c* on the lower surface to about 0.07 *c* on the upper surface. The possibility of protecting this surface during tax-ing and take-off therefore arises, since the fly population decreases rapidly with increasing altitude. During the experiments previously described on the King

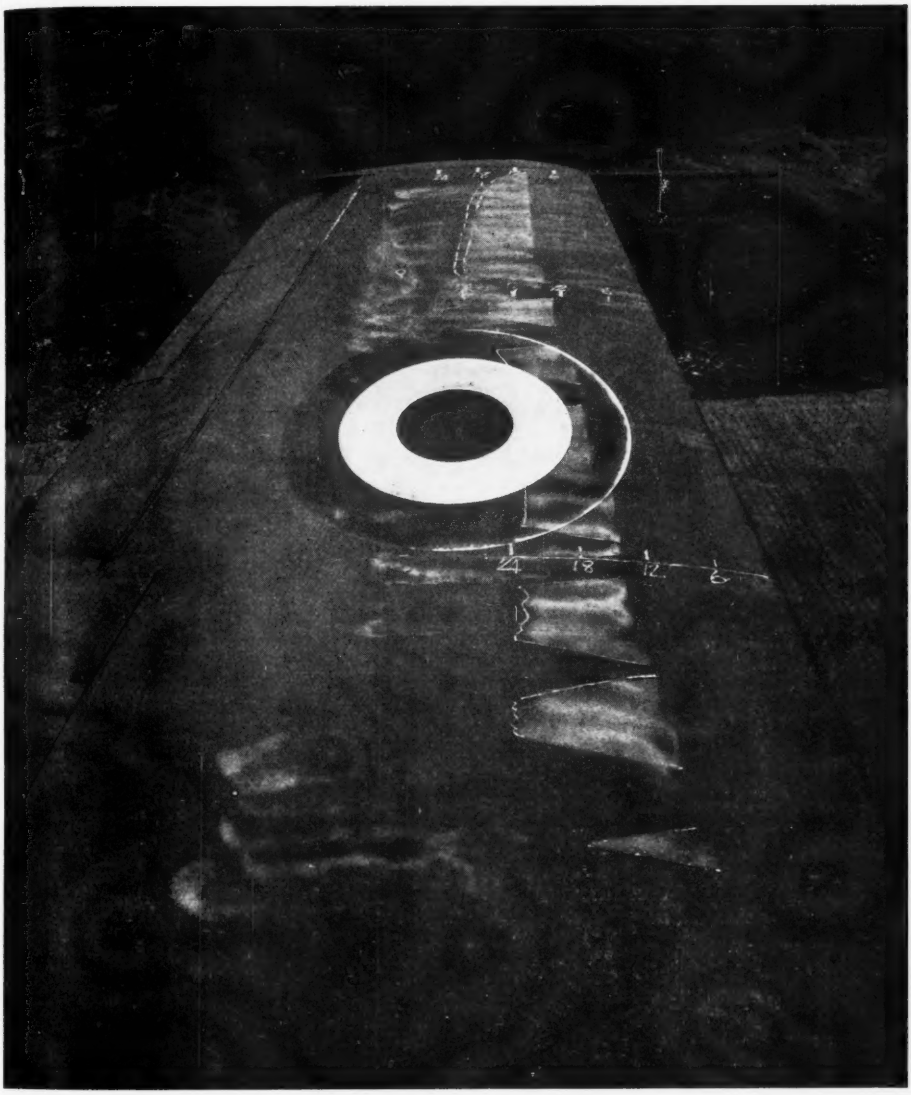


Fig. 10.
Transition on wing of high-speed fighter aircraft—standard finish, L.E. roughness rubbed down.
($M=0.72$, $C_L=0.07$, $R=34\times10^6$)

Cobra at the R.A.E., some tests were made with a paper cover stretched over the front part of the test section and extending to about $0.3c$ on both surfaces. The paper was fastened to the wing round its edges and was ripped off after take-off by pulling a string passing from the cockpit round the paper at the leading edge. This method proved quite successful but its application to the complete wing of a large aircraft obviously would be more difficult.

An attempt has also been made to coat the

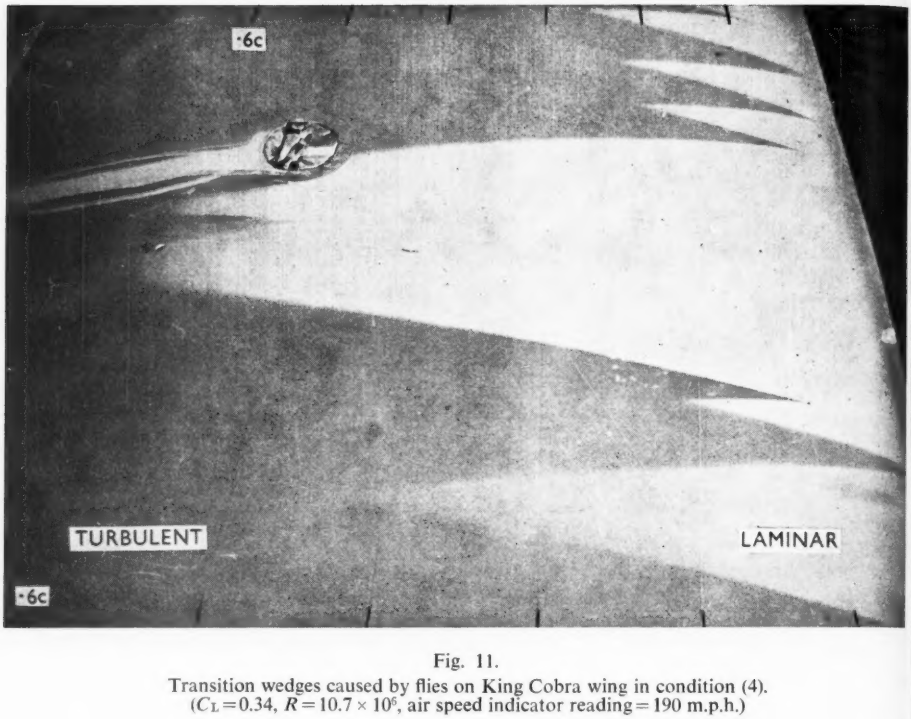


Fig. 11.
Transition wedges caused by flies on King Cobra wing in condition (4).
($C_L = 0.34$, $R = 10.7 \times 10^6$, air speed indicator reading = 190 m.p.h.)

wing surface with a volatile solid material such as camphor, which would sublime away in flight, taking the insects with it. This method has not so far been successful.

1.1.5. *Boundary layer suction*

Although a large amount of theoretical and wind tunnel work has been done on boundary layer suction, flight research on this subject has been limited so far, mainly owing to the complication and expense of the preparations needed for such a test. A few interesting experiments have been made in flight and it will be worth describing one of them briefly to illustrate the problems involved.

The tests referred to were made in order to investigate the practical problems involved in applying the now well-known principle of the Griffiths suction wing[5] to an actual aircraft. The outer wings of a Meteor III (*i.e.* outside the engine nacelles) were removed and replaced by special sections of the form illustrated diagrammatically in Fig. 12. These sections had a maximum thickness chord ratio of 16 per cent. and were designed to have a favourable pressure gradient almost to 0.75*c*, where there was a suction slot, nominally 0.04 inches deep, formed between the aileron and the wings as shown. The suction was provided by a modification of the blower normally used to cool the rear bearings on the Derwent I engines. This should theoretically have given values of suction coefficient C_Q at the slots estimated to be necessary to prevent a separation or rapid thickening of the boundary layer behind the slot, provided the boundary layer remained laminar to somewhere near the slot.

In the form in which the aircraft was first tested at the R.A.E. the suction had no effect on the drag. This was found to be partly due to the fact that the transition on both upper and lower surfaces of the wing, as observed by Gray's chlorine method, was occurring at about 0.06*c*, where there was a ridge almost 0.01 inches high in places caused by a butt joint in the skin. The surface waviness was also of rather a poor standard (see Fig. 13).

With this forward transition the boundary layer thickness at the slot was such that it

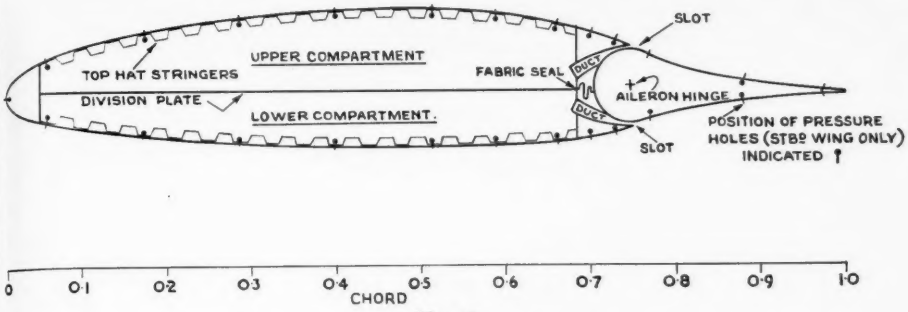


Fig. 12.

Section through Griffith suction wing at test section, as fitted to Meteor III outboard of nacelles.

would have required twice the available suction to produce the desired effect.

The surface, therefore, was painted and rubbed smooth, removing the ridge at the skin joint to negligible proportions, and reducing the waviness to the standard shown in Fig. 13. The transition was then found to be about 0.70*c* on the lower surface and 0.55*c* on the upper surface (at $C_L = 0.2$). The transition was thus slightly aft of the maximum suction on both surfaces (*see* Fig. 14) so that further improvement of the surface would have been unlikely to have had much effect.

Even with this improved surface condition the suction still seemed to have only a small proportion of the expected effect. This was eventually found to be due to the fact that although the air flow through the blower corresponded to a mean value of C_Q at the slots slightly greater than required (0.0006), the local C_Q actually being achieved at the test section was only about half the required value. This loss was found to be partly due to leaks in the duct system and partly to non-uniformity in the spanwise distribution of flow in the slots caused by variations in slot width and by the internal design of the ducts.

Since extensive dismantling and reconstruction of the wings would have been necessary in order to produce sufficient improvement in C_Q, one of the wings was removed from the aircraft and tested in the No. 2 11½ ft. tunnel at the R.A.E. These tests confirmed that when the value of C_Q at the slots was increased to that theoretically required (about 0.0006) the expected gain due to the suction was realised, the section profile drag coefficient being reduced to about 0.002.

The aileron effectiveness, although substantially lower than on a standard Meteor III was considered to be adequate, even with suction off, in spite of the disturbed flow over the aileron surfaces in this condition. There was some aileron oscillation, the severity depending on the upfloat angle. With zero upfloat angle the oscillation was negligible. The longitudinal and directional handling characteristics of the aircraft were the same as those of a standard Meteor.

These experiments, although not entirely conclusive, served to demonstrate the following points in relation to possible applications of the Griffith wing principle.

(1) It is still necessary with this design to achieve a very high standard of surface finish if the transition is to be got near enough to the slot to enable the full advantages of the design to be realised.

(2) The construction of the suction slot and the ducting must be such as to guarantee a reasonably uniform flow distribution in the slot.

(3) Lateral control characteristics can be made acceptable even with suction off, at any rate for the moderate wing thickness of 16 per cent. used in these experiments.

1.2. Measurement of overall drag in flight

The measurement of section profile drag coefficient has already been mentioned. Measurement of the total drag of aircraft in flight is also an important problem. Fortunately it is one of the few problems which has become easier since the advent of jet aircraft, since it is fairly easy to measure the thrust of a turbine engine in flight using a pitot in the jet pipe. The technique is well known[6, 7] and need not be described here. Since the method can be extended to apply

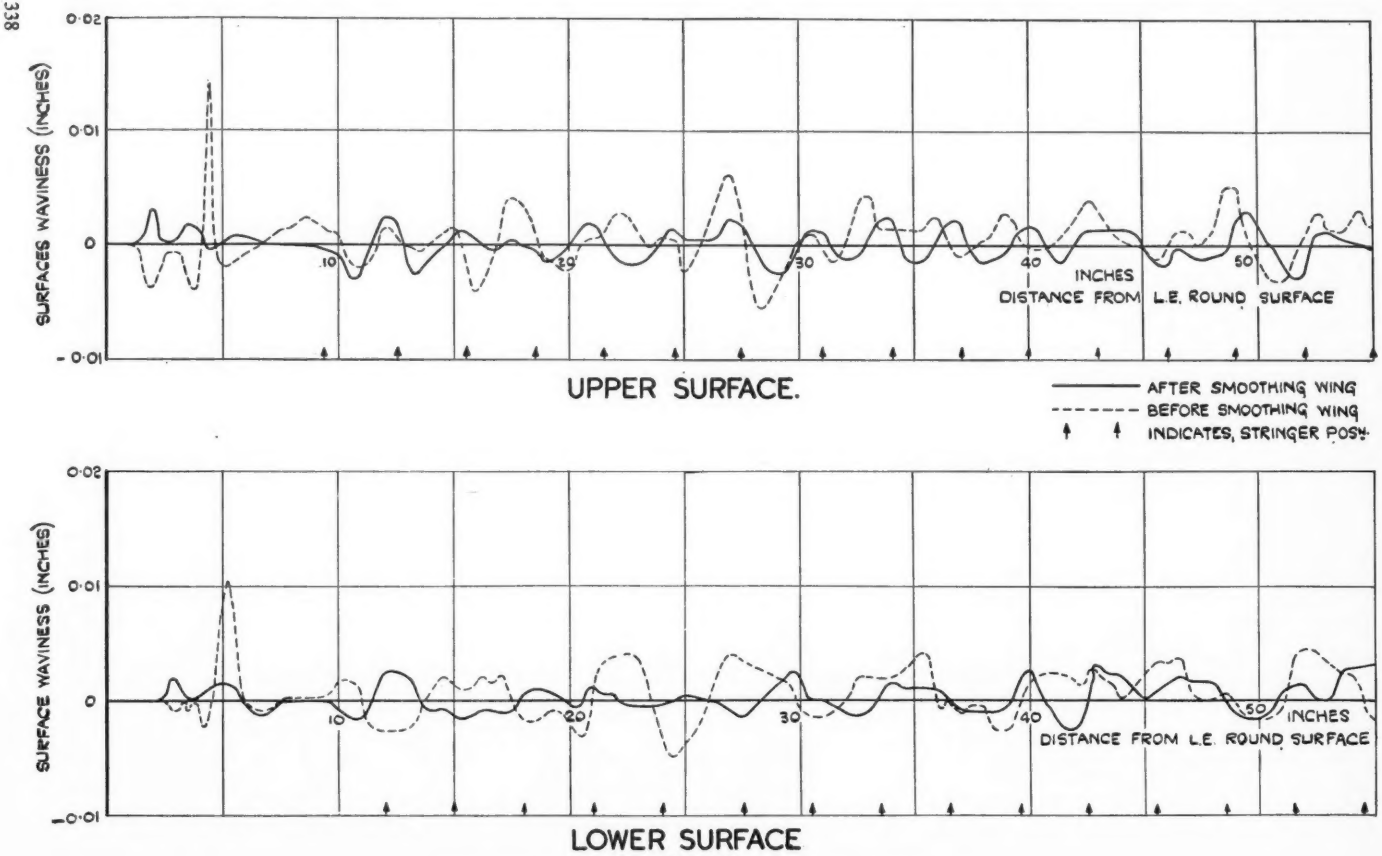


Fig. 13.
Surface waviness of Griffith suction wing at pressure plot section.

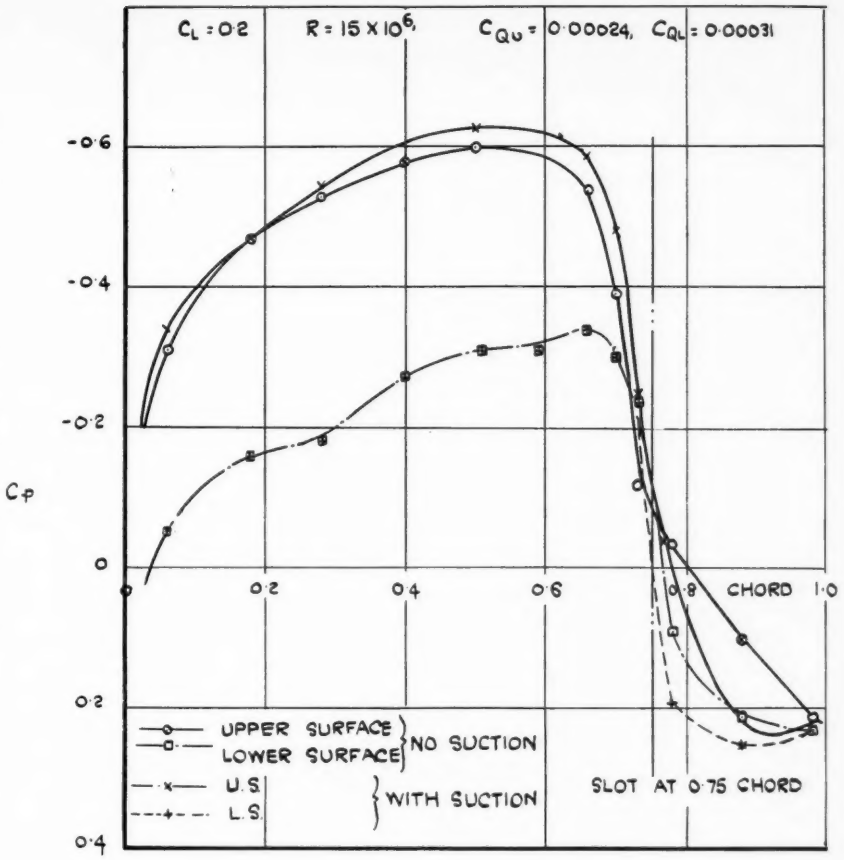


Fig. 13.
Surface waviness of Griffith suction wing at pressure plot section.

Fig. 14.
Pressure distributions on Griffith suction wing fitted to Meteor III (improved wing surface).

in dives as well as in level flight, using a longitudinal accelerometer to determine the acceleration, measurements of drag can be obtained at speeds well above the maximum level speed of the aircraft. The results of some typical measurements are given in Ref. 6.

Perhaps the most important objective of measurements of this kind is to provide a check on wind tunnel tests. Some detailed comparisons of flight and tunnel measurements of the drag rise due to compressibility were made by Hills in a recent lecture[8]. On the whole these comparisons were very encouraging in confirming the reliability of predictions based on wind tunnel tests. Considerable discrepancies might be expected, however, when separation effects are present in the drag. Such effects usually contribute to the increase in drag of an aircraft with increasing incidence, *i.e.* to the so-called induced drag factor K. Unfortunately the measurement of K in flight is not easy, because of the difficulty of separating out the effects of varying Reynolds number and lift coefficients.

Lift coefficient also has an important effect on the drag rise at high Mach number. It is not really possible at these high Mach numbers to represent the effect as a variation in K, since the total drag is no longer even approximately a linear function of C_L.

2. STABILITY AND CONTROL

It is obvious that research and development on aircraft in flight must play an extremely important part in achieving good stability and control characteristics. Not only are the pilots' impressions of the handling characteristics the final criterion by which an aircraft must be judged, but there are still many basic stability and control characteristics which can only be investigated adequately in an actual flight test.

This is again a wide field and an exhaustive survey would be impossible in a lecture of this nature. Therefore the contribution which flight research can make in this field will be illustrated by discussing some outstanding problems in longitudinal, lateral and directional stability, and in the development of controls.

2.1. Longitudinal stability

The problem of achieving satisfactory stability throughout the speed range has been complicated greatly in recent years by compressibility and aeroelastic effects at high speed and by difficulties arising from the use of unorthodox plan forms at low speeds. In the old days pitching moment coefficients usually varied more or less linearly with lift coefficient, so that the static and manoeuvre margins did not often vary widely over the speed range except for occasional interference effects.

At very high speeds large changes in longitudinal characteristics inevitably occur, mainly due to compressibility but often accentuated by aeroelastic effects. The use of sweepback to delay and reduce the compressibility effect, in turn has made it more difficult to retain adequate longitudinal stability down to the stall. Fig. 15 illustrates diagrammatically the sort of variation in static stability which, for example, might be expected to occur on a modern high speed aircraft from the stall up to supersonic speeds. This shows an instability occurring at the lower speeds, changes of trim occurring at transonic speeds involving regions of large negative static margin, and the virtually inevitable increase in static stability at supersonic speeds.

These effects depend on a large number of factors and systematic investigation of them is possible only by wind tunnel tests and by other model techniques. The

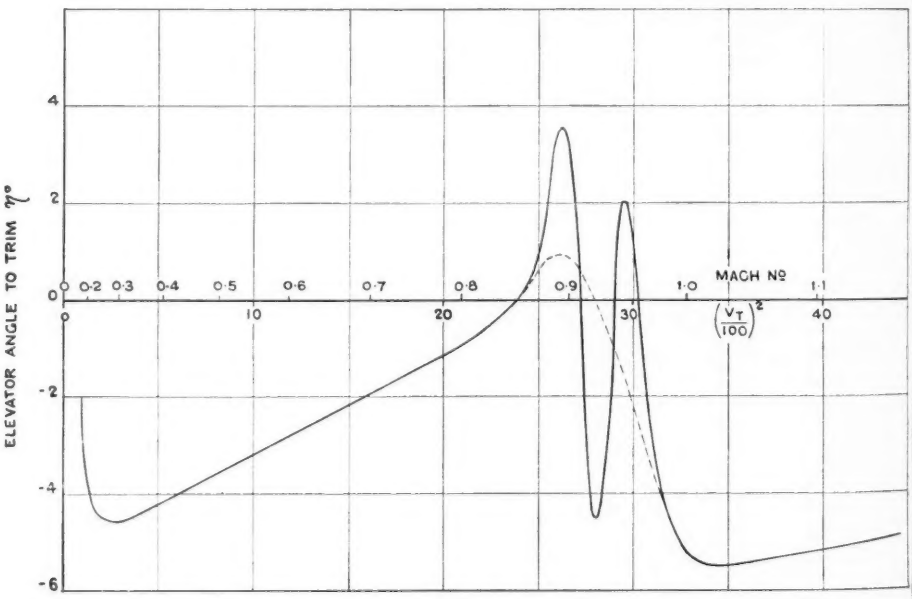


Fig. 15.
Variation of stability which may occur through the speed range.

objectives of flight research in this field must be:—

(*i*) To provide constant checks on the model techniques.

(*ii*) To investigate special effects which are not present, or are difficult to represent fully, in model tests.

(*iii*) To assess the importance of the changes which occur from the pilot's point of view so that the minimum standards to be aimed at in design may be established.

Comparisons of some recent flight and wind tunnel tests were discussed by Mr. Hills[8]. On the whole fairly good agreement was shown when the wind tunnel Reynolds numbers were high enough, and provided that no appreciable aeroelastic or other effects not represented in the tunnel occurred.

These additional effects are often important however. An example is illustrated in Fig. 16. This shows the trim changes which may occur on a Vampire aircraft, and their dependence on the detailed shape of the elevator shrouds. It will be seen that a severe nose down trim change, in this case, was eliminated by comparatively minor modifications to the elevator shroud.

There are many other longitudinal stability characteristics which can be investigated adequately and fully only in flight, particularly in connection with aeroelastic effects and dynamic stability problems.

For the third objective listed, consider precisely what constitutes desirable longitudinal handling characteristics in an aircraft, and what are the limitations imposed on the stability derivatives in order to achieve the handling characteristics demanded by the pilot.

A great deal of work has been done in the past on this subject and certain standards have been laid down. It has been generally agreed, for example, that a positive stick free static margin is essential throughout the speed range, and a static margin of around 5 per cent. is often aimed at. Similarly, limitations have been laid down for stick force per *g*, values outside the range 3 to 8 lb. per *g* being generally regarded as undesirable for fighter aircraft.

Unfortunately, the rapid increase in performance which has taken place in the past few years, and the trend towards unorthodox plan forms, have made many of these requirements incomplete and in some cases out of date.

Consider, for example, the requirements for static stability on high speed aircraft. On all such aircraft, as the Mach number is

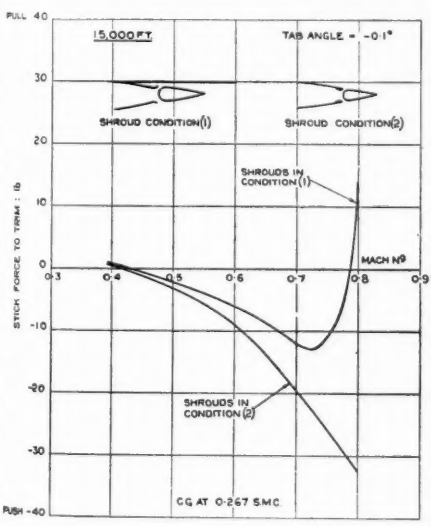


Fig. 16.
Effect of shroud contour on stick forces to trim on Vampire I.

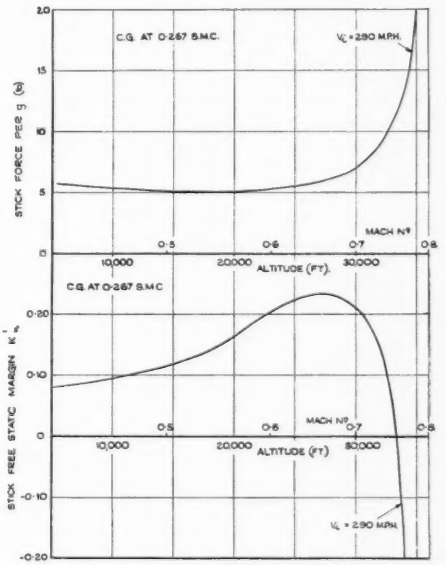


Fig. 17.
Variation of stick free static margin and stick force per *g* with Mach number for Vampire I.

increased, a stage is eventually reached when a more or less severe nose-down trim change occurs. This inevitably means a large reduction of static margin in this region and in most cases, the static margin will become substantially negative. Fortunately this is not accompanied by a corresponding loss of manoeuvre margin; on the contrary, the stick force per g generally increases rapidly in this region. A typical example of the sort of variation which may occur is shown in Fig. 17 by the results obtained in flight tests on a Vampire.

It seems that large negative static margins may be acceptable at high Mach numbers, at any rate for relatively short periods, provided that they are accompanied by positive manoeuvre margins. These conditions, incidentally, are unlikely to arise at low speeds, since a large decrease in static margin at low speed is almost certain to be accompanied by a corresponding reduction in manoeuvre margin.

At high speeds, the important static longitudinal stability requirements seem to be:—

(1) That the manoeuvre margin should remain positive and that the corresponding values of stick force per g should be within the limits previously accepted.

(2) That the trim changes due to compressibility should be gradual, *i.e.* as indicated by the dotted curve rather than the full curve of Fig. 15.

(3) That the trim change should be within the capacity of the pilot either by use of elevator alone or by a combination of elevator and variable incidence tailplane.

2.2. Lateral and Directional Characteristics

Until comparatively recently the attainment of satisfactory lateral and directional stability characteristics was generally considered to be fairly easy, at any rate at low and medium speeds. Morgan, in his lecture to the Anglo-American Aeronautical Conference in 1947, for example, pointed out that normally there was a fairly wide choice of dihedral available between the extremes involving reversal in sign of l_v on the one hand, and "Dutch Roll" characteristics on the other.

With the introduction of sweepback and other unorthodox plan forms the situation may not be quite so easy. In the first place the values of l_v and n_v for a particular design are now likely to vary quite rapidly with C_L,

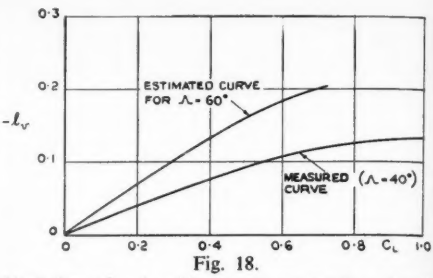


Fig. 18.
Variation of $-l_v$ with C_L on swept wing aircraft.

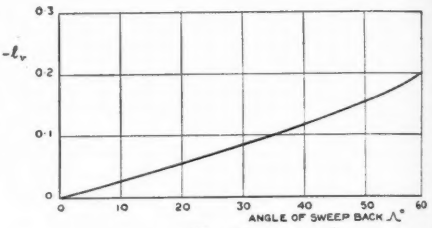


Fig. 19.
Variation of $-l_v$ with sweepback $C_L = 0.7$.

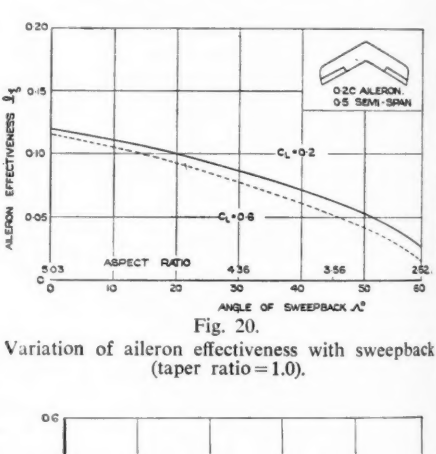


Fig. 20.
Variation of aileron effectiveness with sweepback (taper ratio = 1.0).

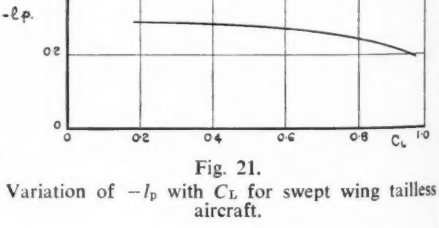


Fig. 21.
Variation of $-l_p$ with C_L for swept wing tailless aircraft.

instead of remaining sensibly constant, as was the case with straight wing aircraft. Therefore it has become more difficult to choose values of dihedral and fin area which will be satisfactory over the whole flight range. Fig. 18 shows, for example, the variation in l_v with C_L measured in flight on a swept wing tailless aircraft. The measurements were made by Duddy at the R.A.E. simply by determining the aileron and rudder angles needed to maintain various angles of sideslip, and measuring aileron power by observing the aileron angle needed to balance lead weights mounted on the wing tips. Estimated values of l_v for 60° of sweepback are also shown in Fig. 18 and the probable order of variation of l_v with sweepback for wings of moderate aspect ratio and taper is given in Fig. 19. These variations are likely to be affected by detailed design and are given only to provide a rough background to the following discussion.

Sweepback also results in a reduction of aileron effectiveness, at any rate for conventional aileron design. Fig. 20 shows, for example, the way in which aileron effectiveness is likely to vary when the sweepback is increased by swinging the wing round a pivot on the aircraft centre line, the aspect ratio varying as shown on the abscissae of the diagram.

Finally, the small aspect ratios often associated with sweepback and the tendency towards tip stalling on swept-back wings is liable to result in low damping in roll, particularly at low speeds. Fig. 21 shows the variation in l_p with C_L measured in flight on a swept wing tailless aircraft. Even at low lift coefficients, the value of l_p is lower than is usual on an aircraft of this type, and there is an appreciable further reduction at high lift coefficients. This reduction is likely to worsen with increased angles of sweepback.

It is obvious that these effects are likely to lead to some difficulty in achieving ideal lateral and directional handling characteristics. The high values of l_v likely to occur at low speeds, for example, together with the low values of l_p, may tend to result in badly damped "Dutch Roll" oscillation.

Evidence of low damping of "Dutch Roll" oscillation has occurred on swept wing aircraft in flight (*see* Ref. 9). These aircraft do not in fact satisfy the well-known requirements for the damping of lateral oscillations. British requirements specify that any lateral or directional oscillations should be damped to half amplitude in one complete cycle. American requirements are slightly less severe, as indicated in Fig. 22[10], but both requirements demand a fairly heavy damping. It is clearly important then to re-examine these requirements in the light of present trends in aircraft design. A certain amount of flight research has been done already on this problem in this country and in the U.S.A. This work has suggested that it may not be possible to express the requirements adequately in the simple form indicated in Fig. 22.

Experience on a swept wing tailless aircraft in Great Britain, for example, showed that although a divergent "Dutch Roll" occurs at approach speeds, the amplitude doubling in about 4 cycles, with a period of about 4.5 seconds the pilots did not consider these characteristics to be unacceptable. It seemed that they were able to cope with oscillations of this fairly long period without difficulty.

A rather similar conclusion was reached in some interesting experiments by the

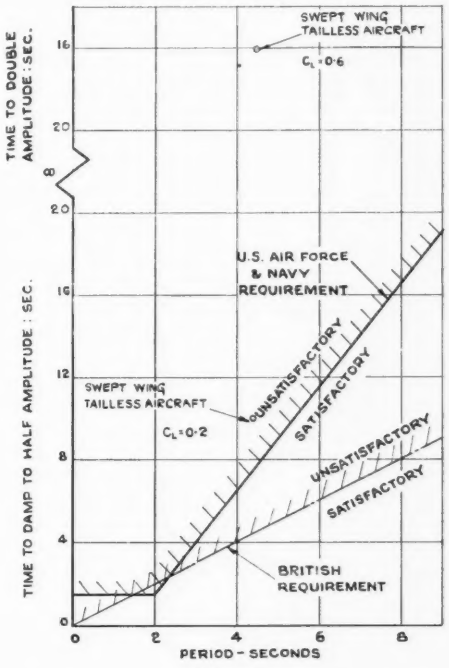


Fig. 22.
Requirement for damping of lateral-directional oscillations.

N.A.C.A. using a conventional straight-winged aircraft and simulating the effect of varying l_v by servo-actuation of the ailerons through a differential linkage in proportion to the deflection of a sideslip vane[10]. These tests suggested that for an assumed approach speed of about 90 knots and a simulated l_v of about -0.29 the handling characteristics were still considered to be good, in spite of the fact that the time to damp to half amplitude was about three times the period. Even with a simulated l_v of -0.37 corresponding to a dihedral of about 28°, the characteristics were still thought to be tolerable in spite of the fact that in this case the oscillations were divergent, the amplitude doubling in about 10 cycles. These experiments also suggested that the ratio of the amplitude of the rolling velocity developed in the oscillation to the amplitude of the sideslip might be an important criterion. At a flight speed of 180 knots, for example, a simulated l_v of about -0.32, resulting in an oscillation damping to half amplitude of about $2\frac{1}{2}$ cycles, was considered unacceptable. This was thought to be due to the fact that the ratio of rolling to sideslip amplitudes was much greater than at the lower speed of 90 knots.

It must be emphasised that the foregoing remarks, which seem to suggest that the damping requirement might be relaxed, apply only to small aircraft, operating in good visibility and weather, and are subject to the condition that the period of the oscillation shall be large enough for the pilot to cope with easily. It is probably more difficult for the pilot to cope with a badly damped "Dutch Roll" on a very large aircraft even when the periods are correspondingly longer, owing to the slower response of such an aircraft to correcting actions. It also seems probable that for blind or bad weather landings a standard of damping at least as good as that suggested by the British requirement (Fig. 22) is still essential. This is confirmed by American experience on at least one aircraft[9]. In this case the "Dutch Roll" oscillations were slightly convergent, and in fact nearly met the American requirements. They were considered, however, to be undesirable, even though the period was quite high (about 7.5 secs.).

The periods of the oscillations in the experiments described were in every case greater than three seconds. It is probable that the lowest period with which a pilot can cope by using his controls is of the order of two or three seconds, although this limit must depend to some extent on size of the aircraft and the precise nature of the oscillation. For periods of less than two seconds, therefore, the damping requirements at least equivalent to those given in Fig. 22 become essential, regardless of weather and visibility. Periods as low as this are not very likely at approach speeds, but they may occur frequently at high speeds, and a new factor then enters into the problem for military aircraft, namely, the standard of damping needed in order to give satisfactory fighting qualities. It is probable that under these circumstances damping to half amplitude in one cycle is not good enough. It is not easy with present design trends to achieve the desired standard. Automatic means of increasing the damping to meet this problem have been developed and the early work of Dr. Doetsch at the Royal Aircraft Establishment in this connection was described in in Ref. 11. Since then extensive flight tests have been made in this country to improve these artificial damping devices. The method can also be used to prevent "Dutch Roll" at low and moderate speeds[9].

The fact that the dynamic stability characteristics of an aircraft can be improved artificially in this way should not be allowed to encourage any relaxation in the efforts to achieve satisfactory characteristics by purely aerodynamic means. It should be regarded rather as an insurance against failure caused by our incomplete knowledge of the effects of present design trends on the stability derivatives.

Summarising the foregoing paragraphs on the damping of lateral oscillations, it may be tentatively suggested, on the basis of recent flight experience, that:

(1) For small aircraft operating in reasonably good weather and visibility, the degree of damping may not necessarily have to be as good as that suggested in the present requirements (Fig. 22), provided the period of the oscillation is not less than about three seconds, and provided that the ratio of roll to sideslip amplitudes in the oscillation is not large.

(2) For large aircraft, or for blind landings, a standard of damping at least equivalent to that specified in the British requirement is desirable, even if the periods are large.

(3) For oscillations of short period, such as may occur at high speeds, greater

damping than that indicated even in the British requirement is desirable.

There is a further consequence of the variation in l_v with C_L and the reduction in aileron effectiveness on swept wing aircraft which has not yet been mentioned. These two effects together result in an increase in the aileron angle needed to hold the aircraft level in a sideslip. Fig. 23 shows the order of the increase in aileron angle per degree of sideslip as the sweepback is increased by swinging the wing about a pivot on the centre-line. For the angles of sweepback which have been used on existing aircraft (*i.e.* up to about 40°) the effect is not serious (about 10° of aileron for 5° of sideslip). Experience with these aircraft has confirmed that although the effect is noticeable, it is not difficult to cope with. For much greater angles of sweepback, however, it seems probable that the effect would become unacceptable, particularly in connection with cross-wind landings and take-offs, unless some means of increasing aileron effectiveness is adopted.

2.3. Flight Research on Controls

The development of controls and associated devices such as air-brakes, *g*-restrictors, and so on, has always been an important objective of flight research. The extensive work done in flight in improving hinge moment characteristics and in achieving satisfactory stick free stability is well known and was discussed in the lecture by Morgan and Thomas in 1945[12]. More recently valuable work has been in flight in developing power controls, servo-tabs and *g*-restrictors. This aspect of flight research and the conclusions derived from it have been discussed in two papers by Lyons[13, 14].

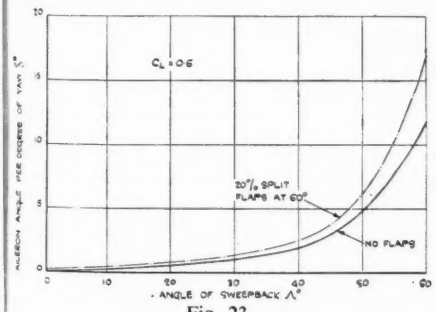


Fig. 23.
Variation with sweepback of aileron angle needed to trim out 1° of sideslip.

For the purpose of this lecture as an illustration of the contribution which flight research has made in this field a special problem will be taken which has recently come back into prominence, namely, the development of spoilers for lateral control of aircraft.

The possibility of using spoilers for lateral control, thus freeing the whole of the wing trailing edge for landing flaps, was realised many years ago. Wind tunnel tests indicated that adequate rolling effectiveness could be achieved, but unfortunately early flight tests were not very promising. The main objections arose from:—

(1) Difficulties in obtaining acceptable "feel" characteristics, due either to non-linear hinge moment characteristics or to inertia effects.

(2) The lag which occurred between operation of the spoiler and start of the roll.

(3) The non-linear response characteristics, involving a dead spot at the centre of the aileron travel.

(4) The loss of overall lift which occurs when a spoiler aileron is applied to pick up a wing at low speeds, and the possibility of excessive yawing moment (though in a favourable direction) due to the large drag of the spoiler.

The relative importance of these objections varied for different designs tested, but on the whole they were generally considered to outweigh the advantages of spoilers in permitting the use of full span trailing edge flaps.

Design trends during the past few years, however, have introduced new factors favouring the use of spoiler control. These new factors are:—

(1) The introduction of sweepback has increased the difficulties of achieving high lift coefficients for landing and has placed greater emphasis on the need for high lift devices, such as full span flaps.

(2) The demand for very thin wing sections with very small trailing edge angles for high speed aircraft has increased the difficulties of designing trailing edge controls capable of withstanding the high loads and of coping with the hinge moments involved in the small space available.

(3) The use of sweepback and thin wing sections has increased the aeroelastic problems and in particular has made the

difficulty of avoiding aileron reversal due to wing distortion more severe. In Ref. 15 it is shown that for a typical 35° swept-back wing of aspect ratio 9.4, the rolling effectiveness factor $pb/(2V)$ of a conventional trailing edge aileron may be reduced almost to zero at 600 m.p.h. at sea level, whereas the effectiveness of a spoiler aileron designed to produce the same effectiveness at low speed loses only about 15 per cent. of its effectiveness at 600 m.p.h.

(4) The reduction in control effectiveness which occurs at high Mach numbers with trailing edge type controls may be made less severe by the use of spoilers.

Clearly it is important to review the disadvantages of spoiler controls shown in past flight tests to see if they still outweigh the advantages in the light of these new factors. Consider therefore in more detail the flight evidence which led to the four main objections mentioned at the beginning of this section.

1. *Difficulties in achieving satisfactory "feel"*

In the early flight tests on spoilers, the troubles in achieving satisfactory feel arose from two different factors depending on the type of spoiler. With a hinged type spoiler as tested on a Courier aircraft (*see* Ref. 16) great difficulty was experienced in producing reasonably linear hinge moment characteristics with deflection. None of the modifications tested gave really satisfactory results.

Subsequent tests in Great Britain on an American aircraft, the Vought Kingfisher, fitted with a slot lip type spoiler showed that with this design an approximately linear variation could be obtained. In this arrangement a slot is cut in the wing immediately behind the spoiler hinge, and a scoop is then linked to the spoiler in such a way as to admit a varying flow of air through the slot as the spoiler opens, thus enabling the hinge moment characteristics to be varied by altering the linkage between the scoop and the spoiler (*see* Fig. 24).

Later experiments on a Falcon aircraft showed that the hinge moment trouble could also be avoided by using circular arc type spoilers, provided they were carefully designed with their hinge lines at the centre-line of the arcs. In these circumstances the aerodynamic hinge moment could be made practically zero, but inertia effects were then found to be unpleasant, making small rapid control movements difficult.

This type of spoiler was used with considerable success on an American night fighter, the Black Widow[17]. In this case the spoilers were combined with a small feel aileron (*see* Fig. 25). Flight tests at the R.A.E. on this aircraft showed that although the hinge moment characteristics were satisfactory and the effectiveness of the control very good, there were considerable inertia effects. A similar arrangement tested in this country on a Halifax aircraft proved reasonably satisfactory from the feel point of view, but at speeds below 130 m.p.h. the rolling moment produced by the spoilers was greatly reduced and there was appreciable lag.

It is seen then that the problem of achieving satisfactory feel with spoiler control is still a matter of some difficulty, although the problem is not insuperable. There is the

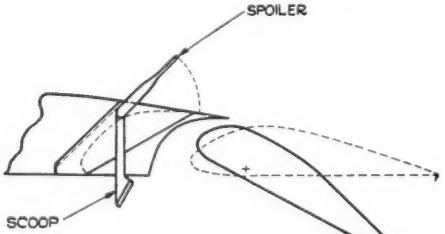


Fig. 24.
Slot-up aileron on Vought Kingfisher.

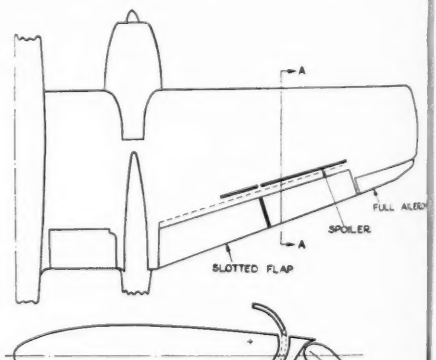


Fig. 25.
Retractable arc spoiler on Black Widow.

possibility of using power control, a complication which is accepted for other control surfaces on most advanced aircraft.

2. *Lag*

The lag between operation of the spoiler and development of the roll depends on the fore and aft position of the spoiler, decreasing with backward movement—and it can also be reduced by venting behind the spoiler. In the flight tests mentioned on the Vought Kingfisher the lag amounted to only about 0.05 second. Lag was also found to be negligible in the Black Widow tests, as well as in some flight tests on a plain hinged spoiler mounted at about 0.6 chord on a small experimental aircraft fitted with a drooped slotted aileron.

3. *Non-linear response*

This difficulty arises from the fact that in general a plain spoiler does not begin to produce an appreciable rolling moment until it has projected a distance of the order of 0.02 of the wing chord above the wing surface. The difficulty can be removed entirely, at any rate for circular arc spoilers, by venting behind the spoiler (*see* Ref. 15). There is also the possibility of altering the gearing to give a large rate of movement of the spoiler near the neutral position, though the inertia problem would probably be worsened by this device.

4. *Loss of overall lift and excessive yawing moment*

No quantitative observations of these effects have been made, but they may constitute the most serious objection to the use of spoilers. It is possible, in fact, that much of the unpopularity of spoilers with pilots, especially in rough weather, arises from the loss of overall lift which occurs when the spoilers are applied. The yawing moment difficulty could be overcome by designing spoilers which operate on the lower, as well as the upper, wing surfaces.

It will be seen then that while flight tests on spoiler controls in the past have not been very encouraging, they do not rule out the possibility of designing spoilers which may be reasonably satisfactory. In view, therefore, of the greater arguments in favour of lateral controls of this type arising from the use of sweepback and other design trends, there seems to be a case for reconsidering the use on modern designs and perhaps for further flight research to investigate the points which remain doubtful.

3. GENERAL AERODYNAMIC RESEARCH IN FLIGHT

The investigation of more or less fundamental aerodynamic problems in flight is not easy but valuable work undoubtedly can be done in this field. It is also possible to use aircraft simply as an alternative means to a wind tunnel of providing the air flow in which to test models. Two examples which illustrate the sort of work which can be done in this connection will be discussed briefly. Both are concerned with the investigation of compressibility effects. The first concerns the detailed investigation of shock wave characteristics in flight; the second concerns a method of investigating aerodynamic characteristics at transonic speeds by mounting small models in the region of high speed flow on an aircraft wing.

3.1. Flight Research on the Characteristics of Shock Waves

In order to understand fully the nature of the compressibility effects which occur on an aircraft it is desirable to examine in detail the characteristics of the air flow round the aircraft. The usefulness, for example, of methods of photographing or visualising the shock waves on an aerofoil has been recognised in wind tunnel work. The application of these methods to the study of the inter-action between the shock wave and the boundary layer, particularly by Ackeret and by Liepmann is an outstanding example of the value of such methods. All this wind tunnel work has been done at low Reynolds numbers and the need to extend the investigation to the Reynolds numbers and conditions of full scale aircraft is obvious. Many attempts therefore have been made to devise methods of photographing or visualising shock waves in flight, and two interesting methods have been developed recently by Dr. Lamplough at the Royal Aircraft Establishment.

The principle of the first, known as the "Contour Method," is illustrated diagrammatically in Fig. 26. A small light source is arranged to move chordwise in a Perspex fairing mounted on the wing surface. Light from this source pours through a chordwise slit in a fairing mounted as shown and is

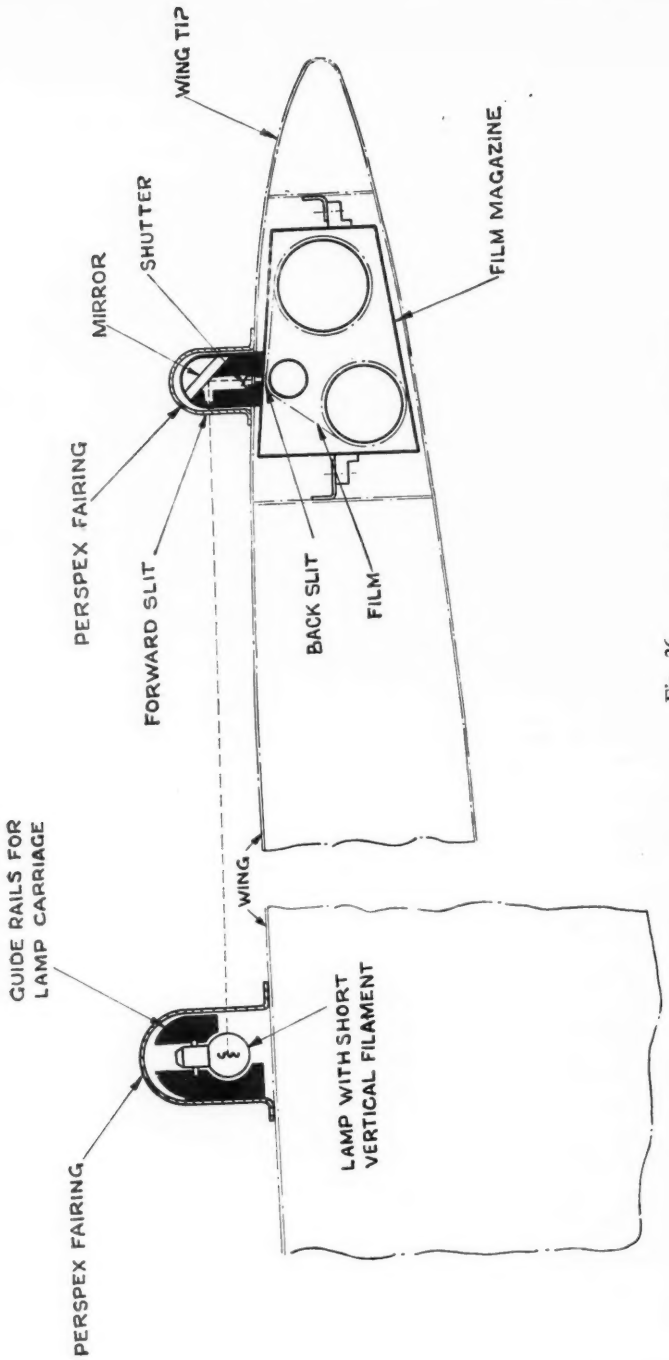


Fig. 26.
Diagram of installation for records to give contour of shock wave on Vampire.

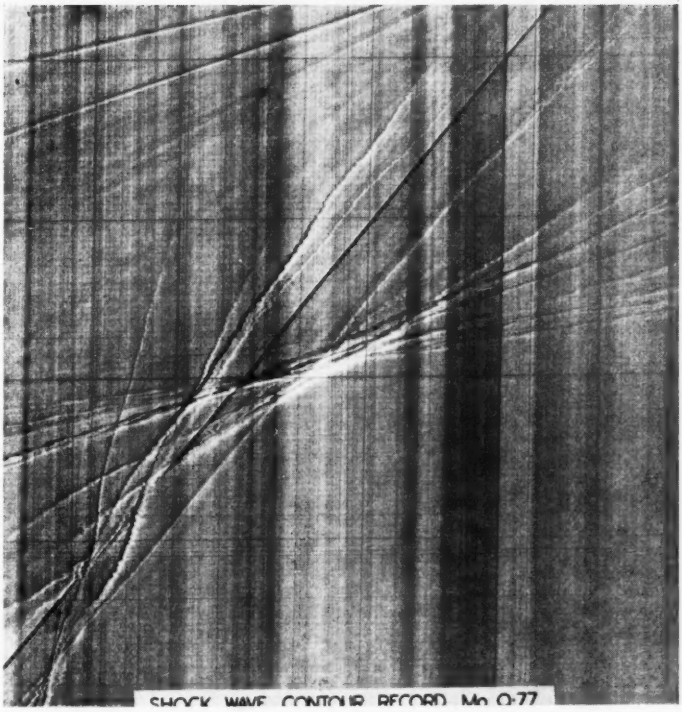


Fig. 27.
Shock wave contour record on Vampire wing at $M = 0.77$.

reflected by a mirror inside the fairing through another parallel slit on to a photographic film which moves in a spanwise direction. Thus any obstacle placed on the wing surface between the light and the fairing will produce a diagonal shadow on the film. Similarly any discontinuity in pressure, such as occurs at a shock wave, will produce a trace on the film.

Figure 27 shows a typical record obtained with this technique on a Vampire. The record suggests that the shock wave is of "corrugated" form, each of the wavy diagonal traces on the film coming from one of the corrugations. The slope of each of the diagonal lines indicates the spanwise position of the corresponding corrugation in the shock wave. The waves in the diagonal traces indicate that the whole shock wave is oscillating chordwise at a frequency of the order of 30 cycles per second, with very small amplitude.

The straight diagonal lines on the film indicate the existence of pressure discontinuities ahead of the main shock and fixed in position, *i.e.* not oscillating. These were found to correspond in position to the rivets near a skin joint at the front spar.

It will be seen that this method is particularly applicable to the investigation of any phenomena involving shock wave oscillation, or to the location of small shock waves caused by imperfections in the wing surface, as well as the main shock itself.

The method does not, however, enable the nature of the shock wave itself to be examined, nor its inter-action with the boundary layer, and an attempt has been made to develop a method of obtaining "profile" photographs of the shock waves in flight.

In this method a parallel beam of light $2\frac{1}{2}$ inches high by 5 inches wide, from an astrograph bulb and collimating lens, is projected along the plane of the shock wave and then condensed through a small aperture into a

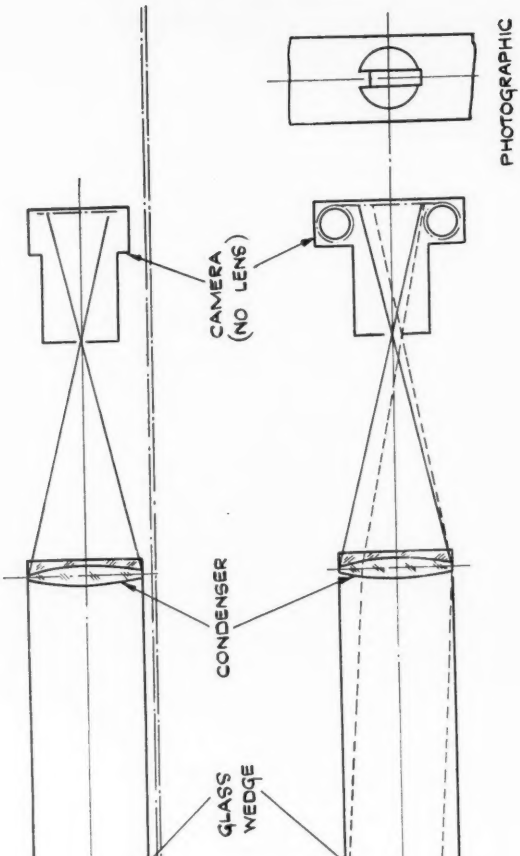


Fig. 28.
Diagram of installation for profile photographs of shock wave on Vampire.

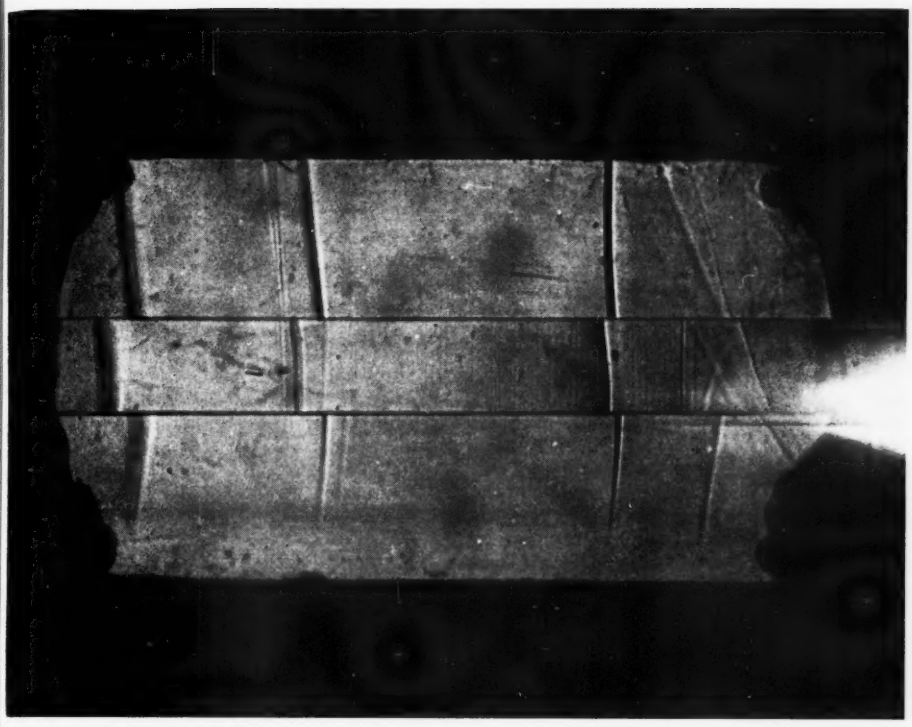


Fig. 29.
Shock wave profile record on Vampire wing at $M = 0.77$.

Robot camera without a lens (*see* Fig. 28). Fig. 29 shows a typical result obtained by this method. The photographs are complicated by the presence of shock waves arising from the lens installations, but it is possible to locate the spanwise position of the shock waves from the lateral shift of the shadows in a small band of light passing through a glass wedge near the collimating lens.

When the photograph shown in Fig. 29 was taken the boundary layer was turbulent at the shock wave, and its thickness is clearly seen. Attempts have been made to improve the wing surface so as to get the transition back to the shock wave, but so far without success.

The potential usefulness of both these methods is obvious, not only for basic research on shock wave characteristics under full scale conditions, but also to locate and investigate the effects of local shock waves on particular aircraft. The methods were described by Dr. Lamplough[21], to whom credit for developing these difficult techniques is due.

3.2. Tests on models mounted on aircraft

The possibility of obtaining useful aerodynamic data by mounting models in the air flow round an aircraft in flight is obvious and the method has been used occasionally in the past. Perhaps the most interesting application of the method is that in which small models are mounted above the wing surface of a high speed aircraft, in the region where the flow becomes supersonic when the aircraft itself is flying at high subsonic Mach numbers. In this way the aerodynamic forces on the model can be measured through the transonic speed range.

The disadvantages of the method are the low Reynolds number of the tests (rather less than one million) and the difficulty of obtaining a sufficiently uniform velocity distribution in the region of the model. On the other

hand the method enables systematic measurements of lift, drag and pitching moment and possibly damping derivatives to be made as in a wind tunnel, and thus provides a means of supplementing results obtained from free flight experiments without going to the lengths of modifying one of the few available high speed tunnels to operate in the transonic speed range.

For these reasons the method has been used in the U.S.A.[18] and in Canada using North American P.51 (Mustang) aircraft and in Great Britain using a Vampire.

On both these aircraft it was found necessary to modify the wing section by means of a "glove" over a short length of the span in order to provide a region of reasonably uniform pressure gradient at transonic speeds. Figs 30 and 31 show the distribution on the surface of the plane wing of the Vampire, and over the glove which was eventually designed for the aircraft (Fig. 32). With this glove there is still a variation of the order of 0.009 in Mach number per inch, in the worst case, but experience so far suggests that in spite of this, reasonably reliable results can be obtained, at any rate for wings of not more than about four inches semi-span and fairly small aspect ratios.

The models are mounted on a turntable flush with the surface of the glove, and the forces on it measured by means of a three component strain gauge balance mounted inside the wing.

The results obtained with this technique have been in fairly good agreement at subsonic speeds with wind tunnel measurements made at the same Reynolds numbers. There has also been reasonable agreement with free flight and full scale tests in the few cases where comparisons have been possible. Figs. 33 and 34 show some comparisons made for a swept wing tailless aircraft and a 90° delta wing.

It seems that the results obtained by the so-called wing flow technique give a reasonable indication of the trends likely to occur at transonic speeds. The method, therefore, can be regarded as a useful, though temporary means of supplementing transonic measurements by the free flight model technique until transonic wind tunnels capable of operating at higher Reynolds numbers become available.

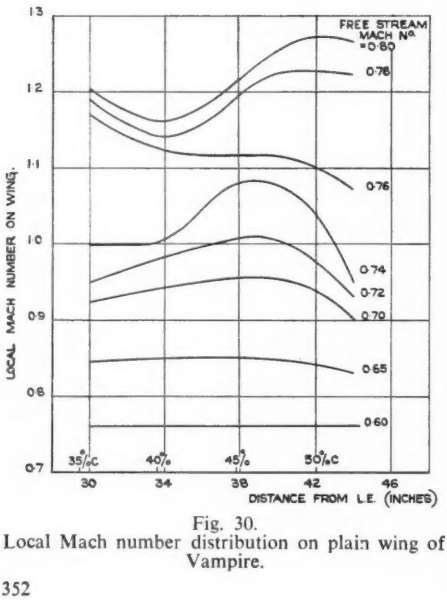


Fig. 30.
Local Mach number distribution on plain wing of Vampire.

4. RESEARCH AIRCRAFT

As have been seen from the examples given, there are three classes of aircraft used in flight research:—

(1) Standard operational or Service aircraft, such as Meteors and Vampires.

(2) Standard aircraft modified in some way to enable particular lines of research to be pursued.

(3) Purely experimental aircraft, designed and built solely for research.

Many aircraft of the third class have been built in recent years. Outstanding examples in Great Britain have been the Armstrong Whitworth 52 built for research on tailless and all-wing designs; the de Havilland 108, also built for research on a tailless layout but particularly to investigate the effects of sweepback; the Avro 707 and Boulton Paul P.111, designed for research on the so-called Delta plan forms; the Hawker P.1052 and Supermarine Swift were also built as research aircraft. Many pure research aircraft have been built in the U.S.A. also, such as the supersonic rocket-propelled Bell XS-1; the Douglas Skyrocket and Skystreak, and the Republic XP-91, all designed for research on sweepback, and the well-known range of experimental tailless aircraft built by Northrop[19].

There have been many research aircraft also belonging to Class (2) above, such as those mentioned in the sections of this paper

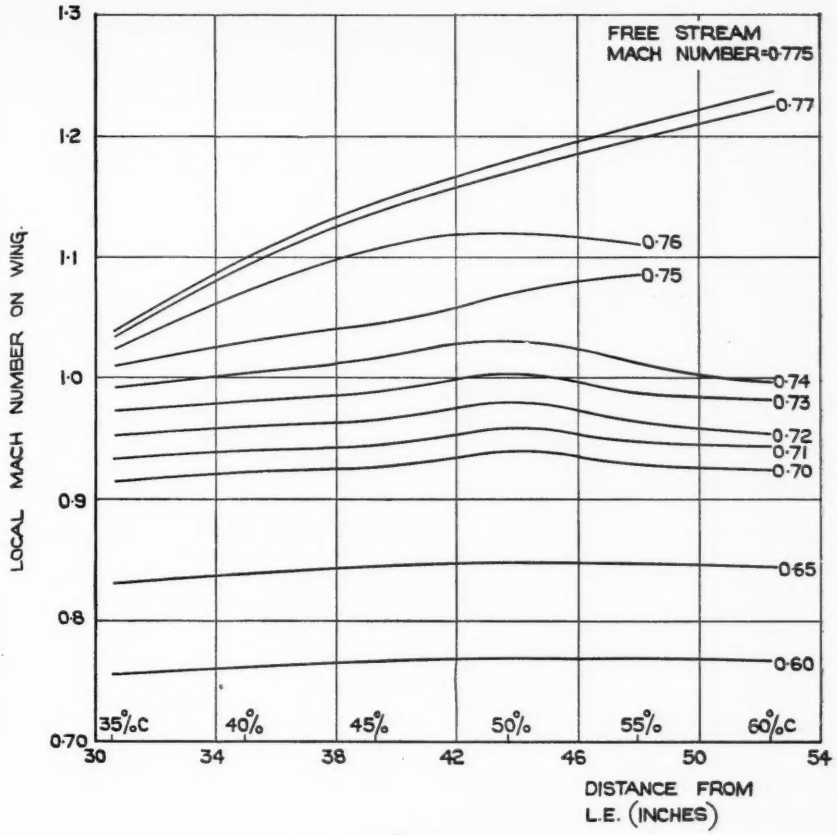


Fig. 31.
Local Mach number distribution on bulge fitted to Vampire wing.

dealing with spoiler control and boundary layer research.

It is suggested sometimes that research aircraft of these types do not repay the undoubtedly great expense involved in designing and building them. Nothing could be further from the truth. The general background of actual flight experience provided by such aircraft is undoubtedly of incalculable value, not only in pointing the way to improvements in the design of Service aircraft, but also in drawing attention to problems which may need fuller investigation by other methods. Occasionally the results obtained from a research aircraft are somewhat negative in the sense that they indicate the particular approach being investigated to be the wrong one. At other times the results give the designer confidence, which no amount of wind tunnel testing could have given, to go ahead with the much greater risks and commitments involved in an advanced production design. In either case the aircraft will have provided information and experience which could not have been got in any other way.

There are three provisos, however. The rate of progress which has to be maintained in these days, both in research and in production, is so great that a research aircraft, if it is to pay its way, must be built in a very short time. It is of little use planning a research aircraft if it is to be four or five years before it begins to provide the necessary experience and data. By that time the risks and gambles which the aircraft is

Fig. 32.
Wing flow-profile shape of bulge fitted to Vampire wing.

designed to investigate will have had to be taken on a production design. It is not easy to design and build a very advanced aircraft in, say 18 months, but a research aircraft has many advantages in this respect. Risks can be taken with less dire consequences than on a production aircraft; the frequent changes in requirements, equipment, and so on, which often delay an operational aircraft should not occur on a research aircraft; and many considerations which affect a production aircraft, such as ease of mass production, maintenance, accessibility of armament, and so on, are not so important.

The second proviso is that once the aircraft has been built, the research work for which the aircraft was intended should have the highest priority, and should proceed with the utmost energy and resource, often to the exclusion of many tests to which a normal service prototype is subject. There may be exceptions to this rule, as when an aircraft capable of easy development to an operational type shows such immediate promise that it is in the national interest to concentrate on converting the aircraft to its operational role. A safeguard against such an eventuality is to provide second and third prototypes following closely on the first, and probably this should be a general policy on all research aircraft.

The third proviso is the obvious one that all the research aircraft to be built should be carefully planned in advance so that the field can be covered as adequately as possible with the minimum number of designs. This is not easy, since it requires a delicate balance between the needs of research as a whole, and the needs of the individual firms concerned who have to build the aircraft. The proviso, however, is particularly important in Great Britain with its limited resources.

If these provisos are fulfilled I do not think there can be any doubt in the minds of either those responsible for research, or those responsible for using the results in designs, as to the value of research aircraft.

5. THE PILOT

It would be inappropriate in a lecture of this nature not to make some reference to the most important link in the whole process of flight testing, namely, the pilot. The success of a flight test is often entirely dependent on the knowledge, skill, and determination of the pilot, and this country is fortunate not only in possessing some of the finest test pilots in the world, but also in having built up an unrivalled organisation for training test pilots of the future.

Few will deny that in recent years the work of the test pilot has been becoming steadily more difficult. Not only have the normal difficulties and hazards of test flying been increasing, owing to Mach number and other new effects, but the problem of understanding clearly the objectives of his work has worsened with the increasing complexity of the test required. It may not be unprofitable, therefore, to state briefly what in the lecturer's opinion are the qualities which are now demanded of an ideal test pilot, from the technician's point of view.

The first requirement is that he should be an exceptionally good pilot on normal standards, quite apart from test flying, capable of accurate flying under all conditions, and above all keen and enthusiastic about flying in general and test flying in particular. He must have the capacity for describing clearly and objectively all that happens in a flight test, keeping an open mind and avoiding whenever possible the temptation to interpret what happens in the light of his own technical background. It is not, for example, desirable for a pilot's report to read: "At a Mach number of 0.9 the lateral stability derivative l_v became positive and there was some evidence that

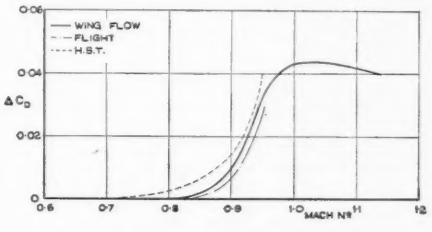
aileron reversal speed was being approached, as well as an indication of a deterioration in l_p." In other words the pilot should always try to describe what happened rather than what he thought caused it to happen. On the other hand he must be willing to try to understand the technical objectives of each experiment, even when the experiment seems to him mysterious and academic. Only a very broad technical background is needed for this purpose, the sort of background which is provided by the Empire Test Pilots' School in this country. Beyond this all that is needed is for the pilot to keep in constant touch with the technicians, taking an active interest in the results being obtained, as well as in the methods and techniques used in the tests themselves. In doing this he must try to maintain a critical outlook, not hesitating to make suggestions or criticisms when necessary. Finally, a requirement common to everyone concerned with experimental work: the ideal test pilot must be capable of a high degree of patience and perseverence. In many tests the necessary accuracy can often only be achieved after long and patient effort on the part of the pilot, while some tests cannot be made at all without a combination of skill and perseverence.

Fortunately these are qualities which are possessed in abundant measure by many British test pilots, and the lecturer would like to take this opportunity of paying a special tribute to all the pilots who have taken part in the work described in this lecture. A very large measure of the credit for this work must go to them.

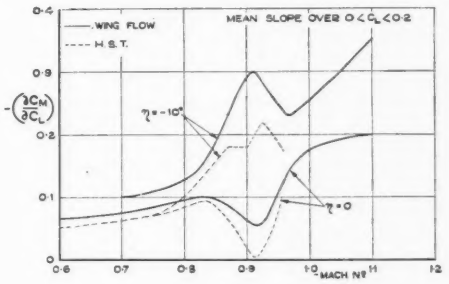
6. CONCLUSIONS

Many important and fascinating aspects of flight research have not been mentioned and many others have been dealt with very inadequately. The extremely interesting work of Milliken and others in the U.S.A. in measuring the stability derivatives of aircraft in flight by the forced oscillation method is one example. This is an application of flight research which has been neglected in this country, but which might repay a little study. Flight research concerned directly with the landing and take-off of aircraft is another extensive field which has hardly been touched upon; nor has any mention been made of stalling and spinning problems. These and many other aspects of flight research have been omitted in the interests of time and space.

Perhaps enough has been said, however, to demonstrate the great part which flight research has played in efforts to extend knowledge and to build better aircraft. Much still remains to be done, and indeed the future, as we move from the transonic to the supersonic era, will hold problems as difficult and as interesting as at any time since the day when it all began, half a century ago.



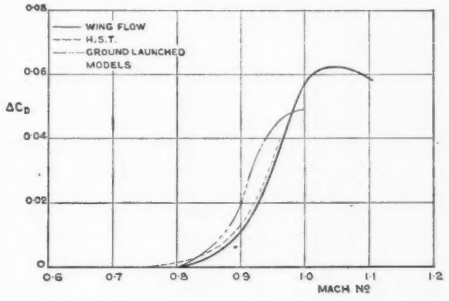
VARIATION OF DRAG INCREMENT WITH MACH NUMBER



VARIATION OF $-\left(\frac{\partial C_M}{\partial C_L}\right)$ WITH MACH NUMBER

Fig. 33.

Comparison of wing flow results with high speed tunnel and flight results for swept wing tailless aircraft.



VARIATION OF DRAG INCREMENT WITH MACH NUMBER

Fig. 34.

Comparison of wing flow results with high speed tunnel and free flight results for 90° delta wing.

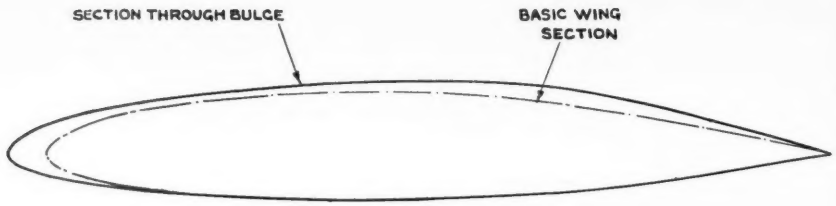


Fig. 32.
Wing flow-profile shape of bulge fitted to Vampire wing.

designed to investigate will have had to be taken on a production design. It is not easy to design and build a very advanced aircraft in, say 18 months, but a research aircraft has many advantages in this respect. Risks can be taken with less dire consequences than on a production aircraft; the frequent changes in requirements, equipment, and so on, which often delay an operational aircraft should not occur on a research aircraft; and many considerations which affect a production aircraft, such as ease of mass production, maintenance, accessibility of armament, and so on, are not so important.

The second proviso is that once the aircraft has been built, the research work for which the aircraft was intended should have the highest priority, and should proceed with the utmost energy and resource, often to the exclusion of many tests to which a normal service prototype is subject. There may be exceptions to this rule, as when an aircraft capable of easy development to an operational type shows such immediate promise that it is in the national interest to concentrate on converting the aircraft to its operational role. A safeguard against such an eventuality is to provide second and third prototypes following closely on the first, and probably this should be a general policy on all research aircraft.

The third proviso is the obvious one that all the research aircraft to be built should be carefully planned in advance so that the field can be covered as adequately as possible with the minimum number of designs. This is not easy, since it requires a delicate balance between the needs of research as a whole, and the needs of the individual firms concerned who have to build the aircraft. The proviso, however, is particularly important in Great Britain with its limited resources.

If these provisos are fulfilled I do not think there can be any doubt in the minds of either those responsible for research, or those responsible for using the results in designs, as to the value of research aircraft.

5. THE PILOT

It would be inappropriate in a lecture of this nature not to make some reference to the most important link in the whole process of flight testing, namely, the pilot. The success of a flight test is often entirely dependent on the knowledge, skill, and determination of the pilot, and this country is fortunate not only in possessing some of the finest test pilots in the world, but also in having built up an unrivalled organisation for training test pilots of the future.

Few will deny that in recent years the work of the test pilot has been becoming steadily more difficult. Not only have the normal difficulties and hazards of test flying been increasing, owing to Mach number and other new effects, but the problem of understanding clearly the objectives of his work has worsened with the increasing complexity of the test required. It may not be unprofitable, therefore, to state briefly what in the lecturer's opinion are the qualities which are now demanded of an ideal test pilot, from the technician's point of view.

The first requirement is that he should be an exceptionally good pilot on normal standards, quite apart from test flying, capable of accurate flying under all conditions, and above all keen and enthusiastic about flying in general and test flying in particular. He must have the capacity for describing clearly and objectively all that happens in a flight test, keeping an open mind and avoiding whenever possible the temptation to interpret what happens in the light of his own technical background. It is not, for example, desirable for a pilot's report to read: "At a Mach number of 0.9 the lateral stability derivative l_v became positive and there was some evidence that

aileron reversal speed was being approached, as well as an indication of a deterioration in l_p." In other words the pilot should always try to describe what happened rather than what he thought caused it to happen. On the other hand he must be willing to try to understand the technical objectives of each experiment, even when the experiment seems to him mysterious and academic. Only a very broad technical background is needed for this purpose, the sort of background which is provided by the Empire Test Pilots' School in this country. Beyond this all that is needed is for the pilot to keep in constant touch with the technicians, taking an active interest in the results being obtained, as well as in the methods and techniques used in the tests themselves. In doing this he must try to maintain a critical outlook, not hesitating to make suggestions or criticisms when necessary. Finally, a requirement common to everyone concerned with experimental work: the ideal test pilot must be capable of a high degree of patience and perseverence. In many tests the necessary accuracy can often only be achieved after long and patient effort on the part of the pilot, while some tests cannot be made at all without a combination of skill and perseverence.

Fortunately these are qualities which are possessed in abundant measure by many British test pilots, and the lecturer would like to take this opportunity of paying a special tribute to all the pilots who have taken part in the work described in this lecture. A very large measure of the credit for this work must go to them.

6. CONCLUSIONS

Many important and fascinating aspects of flight research have not been mentioned and many others have been dealt with very inadequately. The extremely interesting work of Milliken and others in the U.S.A. in measuring the stability derivatives of aircraft in flight by the forced oscillation method is one example. This is an application of flight research which has been neglected in this country, but which might repay a little study. Flight research concerned directly with the landing and take-off of aircraft is another extensive field which has hardly been touched upon; nor has any mention been made of stalling and spinning problems. These and many other aspects of flight research have been omitted in the interests of time and space.

Perhaps enough has been said, however, to demonstrate the great part which flight research has played in efforts to extend knowledge and to build better aircraft. Much still remains to be done, and indeed the future, as we move from the transonic to the supersonic era, will hold problems as difficult and as interesting as at any time since the day when it all began, half a century ago.

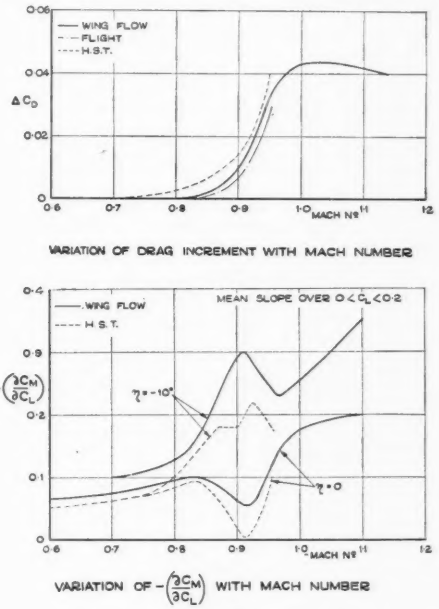
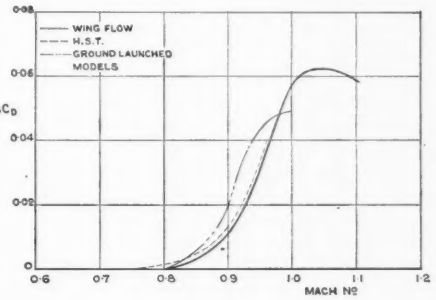


Fig. 33.

Comparison of wing flow results with high speed tunnel and flight results for swept wing tailless aircraft.



VARIATION OF DRAG INCREMENT WITH MACH NUMBER

Fig. 34.

Comparison of wing flow results with high speed tunnel and free flight results for 90° delta wing.

NOTATION AND ABBREVIATIONS

b = wing span
c = wing chord
C_L = lift coefficient
C_D = drag coefficient
C_{D0} = drag coefficient at zero lift
ΔC_D = increase in drag coefficient
C_p = pressure coefficient
C_Q = suction coefficient (suffixes "U" and "L" corresponds to upper and lower surfaces)
C_M = pitching moment coefficient
c.g. = centre of gravity
g = acceleration due to gravity
H.S.T. = high speed tunnel
K = induced drag factor
K'_n = manoeuvre margin
L.E. = leading edge
l_v = rate of change of rolling moment coefficient due to sideslip
l_p = rate of change of rolling moment coefficient due to rolling
l_ξ = aileron effectiveness = rate of change of rolling moment coefficient with aileron angle
M = Mach number
p = rate of roll (radians/sec.)
R = Reynolds number
$\bar{c}$ = S.M.C. = standard mean chord
T.E. = trailing edge
V = forward speed (ft./sec.)
V_T = true speed
V_i = equivalent air speed (m.p.h.)
η = elevator angle
Λ = angle of sweepback
ξ = aileron angle

ACKNOWLEDGMENTS

Most of this lecture has been based on flight tests done by the author's colleagues at the R.A.E., and he would like to acknowledge his indebtedness to them all. He would particularly like to thank R. J. Ross and D. J. Higton for their invaluable assistance during the preparation of the lecture. The opinions expressed are, however, the author's, and do not necessarily reflect the official view of the R.A.E. nor of the Ministry of Supply. The author also thanks the Chief Scientist, Ministry of Supply, for permission to give the lecture.

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DISCUSSION

H. R. Watson (Sir W. G. Armstrong Whitworth Aircraft Ltd.): Mr. Davies had drawn their attention to what he described as defeatism over laminar flow on Service aircraft: that was a matter for the designer, and although he agreed there was some despondency he would like to defend the designers.

They found aircraft were nearly all fast in these days and they had to have the smallest possible frontal area and the smallest internal volume. The whole of this internal volume was filled with equipment. They struggled to get that equipment in and the overworked simile about the quart in the pint pot was an understatement, since the shape of the quart could at least be controlled. Eventually they got the equipment into the aircraft, which was usually about 20 per cent. bigger than when they started; then they found they had to get it out again. This gave rise to an enormous number of access doors all over the wing, the doors having to be both stress carrying and quickly detachable. They gave access to items such as undercarriage, ammunition, control circuits. In their more optimistic moments they hoped that it would be possible to place the doors not too close to the leading edge but in the end they found that the leading edge itself had to be thermally de-iced and access doors were needed to get the soot out.

Although he agreed that laminar flow was needed it was often difficult to realise for Service aircraft.

It was noticeable that the violent fluctuations in the change of elevator angle to trim occurred well below the Mach No. of one; had Mr. Davies found that the relative thickness chord ratios between mainplane and tailplane controlled them to a major extent?

E. D. Keen (Sir W. G. Armstrong Whitworth Aircraft Ltd., *Fellow*): He understood it to be a fact that, in order to achieve laminar flow, a favourable pressure gradient had to be produced which inevitably gave rise to a high local velocity and a low critical Mach number.

Thus, if the theme of the lecture were towards high speed aeroplanes then laminar flow had no real place. Only the long-range aircraft cruising at a comparatively low Mach number could reap the full benefit of laminar flow. Therefore, assuming that the rate of development was as fast as seemed likely, so that even large aircraft would cruise at high Mach numbers in the very near future, was it worth while continuing laminar flow research from a performance point of view alone?

H. F. Winney (Fairey Aviation Co. Ltd., *Fellow*): It seemed to him that the wing-flow method of measuring drag was very useful at the present juncture in the history of wind tunnel development in Great Britain, because it covered a range on speeds for which no other tunnel could cater.

It also seemed that the results obtained so far had been promising. In particular, the velocity over the wing in the position of the model was remarkably uniform. Although the model had to be smaller than was desirable for a number of tests, the method appeared to fully justify the amount of effort which had been put into the development.

In the first picture of the King Cobra, showing the laminar flow extending far back, he had noticed a line across the wing which suggested that there might be turbulent flow starting from that point, but in view of the fact that this supposed turbulent flow had not extended back there might be some other explanation. Could Mr. Davies explain this line?

C. V. Murray (Deputy Chief Engineer, Armaments Division, Sir W. G. Armstrong Whitworth Aircraft Ltd.): With a tailless all-

wing aircraft, despite the advantages of such devices as laminar flow, boundary layer control, which were introduced with the laudable object of reducing drag, they had to have a bigger wing surface because of the inherent limitations of $C_{L\max}$.

Another thing with which they had to contend was the prevention of flies affecting the "super" smooth surface of the wing.

What was the lecturer's attitude towards the development of tailless aircraft as against an aircraft fitted with a tail ?

H. M. Woodhams (Sir W. G. Armstrong Whitworth Aircraft Ltd., *Fellow*): From the practical side, he had suffered from laminar flow wings and flush riveting, and remembered going to considerable trouble with flush riveting on the leading edge of one particular aircraft, and shortly afterwards had to fit rubber sausages on the leading edge to deal with the de-icing problem, and was told that this did not appear to affect the performance of the aircraft.

It seemed to him that what was wanted was a machined wing, as he did not think that they would achieve their ideal by a built-up wing due to the amount of riveting; even with a machined surface it would appear that the "Oldest Designer Known" could stick fly legs on the leading edge and put them back to where they started.

C. Ainsworth Davis (Rolls-Royce Ltd., *Associate Fellow*): The lecturer had referred to a Meteor fitted with special section wings incorporating suction slots. In company with other people whom he thought might be present, he had been concerned in the design of this installation and if security permitted, it would be interesting to hear of the results obtained.

Were the cameras fitted to wings to take pictures of shock waves ordinary cameras, or were some special optical features required ? Some years ago amateur observers of speed record attempts had said that visible shock waves appeared above the leading edge of the Meteor inner wing section. Was this possible ?

R. J. B. Woodhams (A. V. Roe & Co. Ltd., *Associate Fellow*): The lecture had almost renewed his enthusiasm for flight research, but he had found the process of getting aircraft, installation, and weather, all satisfactory, at the same time, quite harassing. Would Mr. Davies tell them his experience on the actual percentage of flying time wasted due to faulty instruments.

There had been a lot of talk about laminar flow, but at cruising speeds induced drag was equally important and recent tests had shown that the induced drag factors were becoming quite large. Was there any serious research taking place to discover the variables controlling the induced drag factor ?

Would Mr. Davies give his opinion on the value of scale flying models ? Although proving in principle the flying qualities of unorthodox aircraft, control characteristics could not be ascertained to any degree of accuracy because of the lower Reynolds number and lift coefficients at the same Mach number. It was impossible to arrange identical flight conditions of Mach number, Reynolds number and lift coefficient for the model as on the full-scale aircraft.

Peter Kahn (*Graduate*): Were there any transonic wind tunnels capable of operating for a Mach number of one ?

S. H. Ellis (Sir W. G. Armstrong Whitworth Aircraft Ltd., *Graduate*): One of the graphs which had been shown illustrated the variation of l_v with C_L: did this involve an estimated value of l_ξ ? Would the lecturer elaborate upon the technique used to determine l_p and l_ξ.

R. Hall (Armstrong Siddeley Motors Ltd.): Had the lecturer obtained satisfactory agreement between engine thrusts measured in flight and the estimated thrusts ?

J. Morris (Flight Research, Sir W. G. Armstrong Whitworth Aircraft Ltd.): He was disappointed that the lecturer had only mentioned in passing the oscillation technique used for determining the aerodynamic derivatives in flight. It seemed to him that that method was the only one available for determining those derivatives through the transonic speed range.

Taking, for example, the longitudinal stability, the method used at present was that developed by Gates and Lyon and as they pointed out themselves, the application of the method was extremely doubtful above the shock stall.

So far as he knew this method had never been checked experimentally at high Mach number, and yet there were many reports from the R.A.E. and Boscombe in which it had been used to determine static and manœuvre margins on aircraft flying at, or near, their limiting Mach number. The oscillation technique did not suffer from the

deficiencies and he was surprised that it had not been tried in Great Britain.

C. A. Mathias (Rotol Ltd.): The lecturer had said that the Reynolds number was an important factor, and the Mach number also was an important factor. Where in the speed range did they drop the Reynolds number and pick up the Mach number?

MR. DAVIES' REPLY

Mr. Watson: He agreed that the practical problems involved in achieving laminar flow on high speed aircraft, and at the same time providing such necessities as access doors and de-icing equipment, were extremely difficult. He did not underestimate these difficulties and sympathised with the hard life of a designer in his attempts to cope with them. The fact remained that the gains which might be obtained by achieving laminar flow were so large that a considerable effort was worthwhile.

There was no doubt that quite a large part of the fluctuation in stability of elevator angle and trim often arose from the tailplane itself, rather than from the wing surfaces, but it was not always possible to separate the effects. The indications were that with a thickness-chord ratio of around 10 per cent. and a sweepback of, say 35°, there were considerable variations in trim and stability originating from the wing and the downwash at the tailplane. Those variations might be accentuated by compressibility effects on the tailplane itself. Merely making the tailplane thinner therefore might give some improvement, but would leave the main effect on the wing and the downwash unchanged.

Mr. Keen: The production of a favourable pressure gradient did not necessarily entail a high local velocity, as had been suggested. On the contrary, an extensive region of favourable gradient implied, in general, a *lower* maximum suction and a higher critical Mach number.

It was true that once they got into the region of transonic speed, where the aircraft were operating in the region of compressibility drag rise, the gain to be obtained even by making the transition move from the leading edge to, say 50 or 60 per cent. of the chord, was proportionately not very large. But when they thought in terms of commercial aircraft they were still some way away, thank goodness, from operating aircraft well into the compressibility region.

Mr. Winny: He should have explained the line in Fig. 6. It arose from the fact that in the course of the tests, when the transition was far back the front part of the wing was wiped before take-off, the object being to reduce the contamination during take-off by insects and particles of dust, and all the mark indicated was that the wipe extended back just to there. The effect of the wipe appeared to produce reaction just in that region but it was an artificial line and had no relation to laminar flow.

Mr. Murray: The development of tailless aircraft produced a wide range of problems, and Mr. Murray had mentioned some of them. The limitation in the maximum lift coefficient available for landing, for example, was an important disadvantage of the tailless layout, but he would like to emphasise that this was due to the difficulty in using flaps on tailless aircraft, rather than to any loss in $C_{L\max}$ due to using low drag wing sections. There were also difficulties in coping with the trim changes over the complete speed range of a high speed tailless aircraft. On the other hand, there was a substantial amount to be gained in drag on an aircraft large enough to be an all wing aircraft, without a fuselage. He thought that in spite of the disadvantages of tailless aircraft, attempts to develop such aircraft should not be abandoned at this stage.

Mr. H. M. Woodhams: He could only sympathise and add once more that the gains which were there to be obtained, if they could obtain them, were so great that it was well worth while carrying on with those investigations. He thought that the attainment of real laminar flow, with transition at, say 65 per cent. of the chord, was impractical at the present time, but it might not be impractical for ever, and some half way house in the meantime was possible. The mere fact that they could not achieve the perfect was no argument for not trying to go half way.

Mr. Ainsworth Davis: It was only the attempt to choose the aspects which he thought would be of general interest which had made him omit the work on the Meteor with boundary layer suction wings. This work was in fact dealt with in the written version of the lecture. The first thing found was the inevitable one that the wing surfaces were not good enough for the transition to be back to the slot near the trailing edge and it had to be back to the slot before the suction became effective. With the transition at the

leading edge it would have needed many times as much suction to produce an extractor action. They spent a long time improving the wing so as to get the transition back, and eventually got it to within two or three inches of the slot. The effect of the suction was then appreciable, but it still did not show the full gain which they had been led to expect from the wind tunnel tests on that sort of wing. The reason was the accumulation of a large number of small defects, which were described in the written lecture and served to illustrate the extreme difficulty of achieving the desired objective in practice on a wing of this type.

The experiment also showed that the aircraft was flyable even with the suction off. He thought that the practical difficulties and the accuracy needed with this type of wing was of a high order and that the standards needed in that sort of design were too high for a practical aeroplane.

The camera used in the shock wave profile photographs was a German robot camera with the lens removed.

The camera used in the first method was specially made to fit inside the wing of the Vampire.

As to whether shock waves could be seen, it was probable that they could see them if they were in the right position. But the thing which most people thought were shock waves were condensation waves. He doubted whether the whole shock wave could be seen in any circumstances.

Mr. R. J. B. Woodhams: He agreed that the business of weather, instruments not being in working order, and aircraft unserviceability, were circumstances which did cause considerable discouragement in flight research, but in spite of them a certain amount of work did go on, and a remarkable record of flying on experimental aircraft had been achieved in Great Britain. That was done in spite of the British weather and all the other problems and he thought flight research paid such dividends that it was worth a big effort to overcome the difficulties.

He agreed that induced drag was important and it was perhaps a pity that for various reasons it had received only passing reference in the lecture. There was no doubt it was one of the important problems at the present time. Work in that connection had been going on and measurements of induced drag had been made on a number of aircraft and had confirmed that induced drag could be very high in some cases, but they did not fully understand the reason. Research was being conducted to try to obtain a fuller understanding of the problem.

His own view was that scale models were worth while, particularly if the aircraft being designed were large and involved several uncertainties and gambles. Then the advantage of having at an early stage a scale model, even though it did not represent fully the characteristics of the aircraft, was well worth while. It might only be a low speed aircraft which had been designed specifically for the sole purpose of investigating the landing characteristics, but in his experience it was often worth the effort and expense involved. He made one proviso and it was that they should be designed and built quickly. It was a waste of effort to build research aircraft if they were to take three or four years to build them. If that occurred the gamble which it was designed to investigate would have been taken before the aircraft flew.

They would have to see in the future that they could plan and build their research aircraft quickly and use them for research, and reduce to the absolute minimum the use of such aircraft for exhibition and display.

Mr. Kahn: There were no useful transonic wind tunnels capable of operating at a Mach number of one in this country.

The fact that the models used in the wing flow technique were only three or four inches span needed to be thought of in conjunction with the fact that the aircraft was operating at fairly low altitude and at high speeds of the order of 500 m.p.h., so that the Reynolds number, which was the thing that mattered in those tests, was about a million. That, in fact, was comparable with the Reynolds number and tests done in many high speed wind tunnels, but those tunnels were not capable of operating at a Mach number of one.

Mr. Ellis: The estimates were made in flight by having weights on the wing, thereby enabling measurements of l_ξ to be made; and by dropping the weight off in flight and measuring the immediate response l_p could be obtained.

In the lecture there were some curves showing measurements of those derivatives made on an aircraft. The development of a technique of that kind for measurements of the lateral derivative in flight was important. The tests he had been discussing were done,

not so much to determine the derivatives for that particular aircraft, but as a means of developing the technique.

Mr. Hall: Measurements of engine thrust made using a single pitot in the jet pipe had shown reasonable agreement with estimated values based on bench measurements of thrust. Similarly, on the practical side in recent years the actual estimation of the drag compared with the drag measurement had been steadily improving, he thought, and, although methods of estimation did not appear to be by any means completely proved, they were at any rate better than they were five or ten years ago.

Mr. Morris: He agreed that the oscillation technique was the only method by which many of the stability derivatives could be determined in flight at high speeds. Unfortunately this method demanded complicated and extremely accurate instrumentation. With the resources available in Great Britain it was doubtful whether it could be used on any of the limited number of advanced experimental aircraft, which were needed for a wide range of research and development work. The use of the method on current aircraft, like Meteors or Vampires, was of doubtful value in his opinion.

He would like on the other hand to remove the doubts cast by Mr. Morris on the value of the more usual stability tests made in steady flight. Measurements of control angles to trim, and stick forces in level flight and in turns and pull-outs were clearly valuable in that they provided a quantitative measure of the overall characteristics of the aircraft. The only point in doubt in the transonic speed range was the interpretation of these measurements in terms of static and manœuvre margins. This doubt was caused by the breakdown in the assumptions of linearity normally made, and it applied equally to the analysis of the oscillation measurements. It did not detract from the value of the measurements of control angles and stick forces in steady flight which were useful in themselves.

Mr. Mathias: His personal view was that they could never drop the Reynolds number. It used to be thought that they could simplify things on the assumption that Reynolds number effects were practically non-existent in the supersonic speed range. There might be some justification for that in the supersonic speed range but there certainly was no justification for it in the transonic range where the inter-action of the shock-wave and boundary layer was undoubtedly important.

THE PRINCIPLES UNDERLYING THE DYNAMIC STRESSING OF AEROPLANES*

by

D. WILLIAMS, M.I.Mech.E., A.F.R.Ae.S.

1. INTRODUCTION

The purpose of this paper is to explain the principles governing the behaviour of structures under transient dynamic loads, such as those encountered by aircraft structures during landing or flying in gusty weather. The paper is intended mainly for the young aeronautical engineer who may not be particularly well versed in this aspect of stress work.

NOTATION

x = distance, along beam (Sections 2-6), across span (Appendix III)
x_1 = distance along beam of reference section (*See* Section 6)
x = displacement in Sections 7-9 and Appendix I and IV
y = spanwise distance from plane of symmetry in Appendix I. (*See* Fig. 7)
y = displacement, elsewhere than in Appendix I
y_1, y_3 = displacements in 1st and 3rd modes (*See* Section 5)
t = time co-ordinate
t_1, T = particular moments in time
m, m_0 = mass per unit length of beam (suffix "0" refers to root section of wing)
m = mass of suspended weight in simple mass-spring system (*See* Fig. 4)
m = equivalent mass at tip (Section 2)
M = whole mass of beam
M_1 = equivalent mass at reference section equal to total distributed load
M_w, M_f = half-span wing mass, and half fuselage mass, respectively
f = frequency (cycles/sec.)
M_0, M_1 = masses of fuselage and wing engines in Appendix III
p = frequency (rad./sec.) = circular frequency = $2\pi f$
p_1, p_n = circular frequency in modes 1 and n
EI = beam stiffness in bending
w = load per unit length
n = number of mode = number of half sine waves in length l
l = overall length of beam; also, in Appendix I, half wing span
a = amplitude of vibration
a_1 = deflection at central reference section in mode (a) of Fig. 2

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*This paper is the basis of a Lecture given to the Southampton Branch of the Society on 1st November 1950.

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K.E. = kinetic energy
v = velocity of element of vibrating system
v_0 = sudden velocity generated while displacement is still zero.
k = spring stiffness = load per unit deflection
K_n = equivalent stiffness in mode n
P, P_0, P_0' = concentrated applied loads
c = damping coefficient, *i.e.* force per unit velocity
c_{crit} = critical damping coefficient that gives dead-beat motion
c', c_0 = local wing chord and root wing chord respectively
$\varepsilon = c/c_{crit}$
ε_0 = value of ε for typical large aeroplane at sea level (*See* Appendix I)
W = wing loading in steady horizontal flight (lb./ft.^{2})
$\alpha = \varepsilon p$
V = flight speed
C_L = lift coefficient
θ = angle of incidence
$dC_L/d\theta$ = slope of lift curve
η = (spanwise distance from plane of symmetry)/(half wing span) [$= y/l$ in Appendix I. *See* Fig. 7]
ρ = density of air (slugs/ft.^{3})
U = work done
F = force
$F(t)$ = force as function of time
$f(\eta) = [(4\eta - 1)/3]^2$ = upward displacement in terms of unit tip displacement (Appendix I)
A, B = constants

2. NATURAL MODES OF VIBRATION

What tends to make the dynamic behaviour of a structure complicated, whether aeronautical or not, is the fact that a structure is a continuous system and therefore can execute simple natural vibrations in an infinite number of ways; in other words, it has an infinite number of degrees of freedom. It is necessary here to define what is meant by simple natural vibration, or normal mode of vibration, as it is usually called.

Consider a uniform beam AB simply supported at each end and set vibrating in the way shown in Fig. 1, where the dotted lines indicate its extreme travel in either

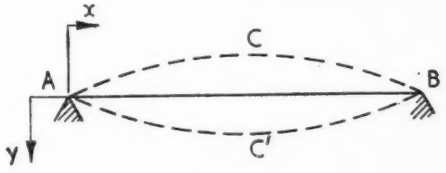


Fig. 1.

direction. The oscillation is a natural or normal mode of vibration if every point executes, in step with all other points, a simple harmonic motion about its equilibrium position at a common frequency. This means that maximum amplitude as well as every fraction of maximum amplitude is reached by all points on the beam simultaneously.

If, at any point x, the full amplitude is y_0, the displacement y at any time t is thus

$$y = y_0 \sin pt, \qquad . \quad . \quad . \quad . \quad . \quad (1)$$

where p is the circular frequency $= 2\pi \times$ (frequency in cycles/sec.).

The corresponding acceleration is

$$f = -p^2 y_0 \sin pt = -p^2 y \qquad (2)$$

and if m = mass of beam per unit length, and

f = acceleration,

the downward inertia force per unit length

$$-mf = mp^2 y. \qquad (3)$$

Thus for *any* shape of displacement curve y specified in terms of x there is a corresponding distribution of inertia loading $mp^2 y$ per unit length, but if the chosen shape is to be constant throughout the vibration, the inertia loading must be equilibrated by the *same* distribution of elastic resistance loading w per unit length. But the elastic resistance loading

$$w = \frac{d^2}{dx^2}\left(EI\frac{d^2y}{dx^2}\right) = EI\frac{d^4y}{dx^4} \text{ (for a uniform beam).}$$

If the right shape is chosen, therefore, at all values of x

Elastic loading = Inertia loading

or

$$EI\, d^4y/dx^4 = mp^2 y. \qquad (4)$$

In the present example the mathematician is able to state that this condition will be satisfied if the displacement curve has any of the shapes given by

$$y = a \sin (n\pi x/l), \qquad (5)$$

where n can have any integral value and the quantity a merely defines the amplitude of the curve.

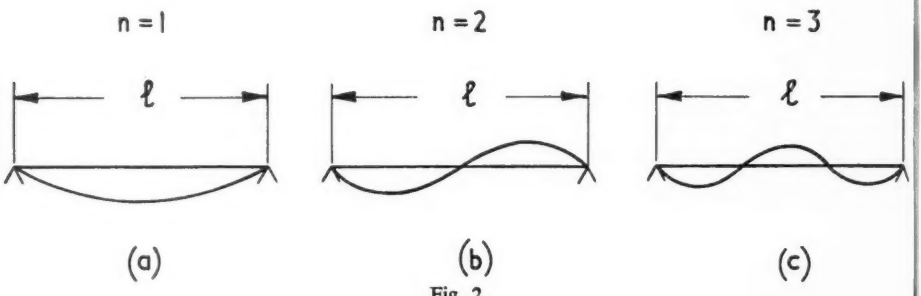


Fig. 2.

Thus, for the uniform beam, the shape that satisfies the definition of a normal mode of vibration is a simple sinusoidal curve forming one, two, three or any number n of loops between the supports. Fig. 2 shows the first three of this infinite series of curves.

The corresponding frequencies can be found at once from (4) which, applied to (5), gives

$$EI\,(n\pi/l)^4 y = mp^2 y$$

or

$$p = n^2 (\pi/l)^2 \sqrt{(EI/m)} \qquad (6)$$

and since

$$p = 2\pi \times \text{frequency}$$

$$\text{frequency (cycles/sec.)} = n^2 (\tfrac{1}{2}\pi/l^2)\sqrt{(EI/m)} \qquad (7)$$

It is seen from this that the frequency goes up with the square of the number of loops, and for the three modes shown, for example, goes up in the ratio 1 : 4 : 9.

3. RESONANCE MODES

The normal or natural modes of displacement given by (5) are identical with the resonance modes of the beam, and when the mathematician fails (as he often does) to find the natural modes, the engineer's only recourse is to find them by experiment—*i.e.* he applies a small oscillating force to the beam and sets it resonating in one normal mode after another. It is known that, to get an appreciable deflection with a very small oscillating load, it must oscillate in time with the natural frequency of the mode that is sought. As both the mode and its frequency are unknown the only thing to do is to start at zero frequency and work up. Every time the frequency of the small oscillating force coincides with a natural frequency the amplitude quickly builds up, and the shape of the beam and its frequency of oscillation are noted. In this way such shapes as Fig. 2 (*a*), (*b*), and (*c*) would be found one after another, together with their frequencies.

It is to be noted that the reason why a resonance mode is identical with a natural mode lies in the fact that, first, all the points in the system move in step, and second, that the vibration is free, *i.e.* there are no forces other than inertia forces. The latter remark is true because the magnitude of the small exciting force is wholly negligible compared with the inertia forces generated.

4. EQUIVALENCE OF EACH MODE TO A SIMPLE SINGLE-DEGREE-OF-FREEDOM ELASTIC SYSTEM

A point to be noted about any normal mode is that the displacement of any one point on the beam is a measure of the displacement at every other point; so that if, for example, the displacement at the middle of a loop is known, the motion of the whole system is defined in terms of that alone. A representative section chosen in this way is usually called a *reference section.*

A particular natural mode of a continuous system subjected to distributed inertia forces and distributed elastic resistance can thus be regarded, in so far as the effect of external forces on amplitude is concerned, as a simple sprung mass in which a single equivalent mass and a single equivalent spring take the place of the distributed forces named. The procedure for determining the value of these equivalent quantities is based on the simple basic principle that any element of force, exerted at any section, can be represented by an equivalent element of force at the reference section. The criterion of equivalence is that the force element does the same amount of work, and hence has the same effect on the amplitude, as it did before transference. An example of the method is shown in Appendix I dealing with damping forces, but, for illustration, the equivalent mass obtained when mode (*a*) of Fig. 2 is defined in terms of the deflection at the mid-point may be determined here. From (5), with $n=1$,

$$\text{Deflection at any section } x = a_1 \sin(\pi x/l) \quad . \quad . \quad . \quad (8)$$

where a_1 is the deflection at the central reference section.

For a small element of mass mdx at x,

$$\text{Inertia force (from (3))} = (mdx)\,p^2 y$$
$$= (mdx)\,p^2 a_1 \sin(\pi x/l) \quad . \quad (9)$$

(where p need not be known since it cancels out later). If this is transferred to the central section unchanged it will do more work by ratio

$$a_1/[a_1 \sin(\pi x/l)] = 1/[\sin(\pi x/l)]. \quad . \quad . \quad . \quad (10)$$

It must be reduced therefore in the inverse ratio so that the work it does is the same. Thus

$$\text{Equivalent inertia force element at reference section} = mp^2 a_1 \sin^2(\pi x/l)\,dx$$
$$. \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (11)$$

Integrating (11) over the whole beam gives the total equivalent inertia force of

$$mp^2a_1 \int_0^l \sin^2(\pi x/l)\,dx = mp^2a_1\,(l/2)$$

$$= \tfrac{1}{2}(ml)\,p^2a_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad (12)$$

$$= \tfrac{1}{2}Mp^2a_1, \text{ where } M = \text{whole mass of beam } ml. \quad (13)$$

If the whole mass M had been transferred unchanged to the centre, the inertia force would be Mp^2a_1, so it is seen that in this case the equivalent mass is half the total mass.

An alternative approach for obtaining the equivalent mass depends on simply equating the sum of the kinetic energy of all the elements of mass of the beam to the kinetic energy of the equivalent mass.

$$\text{Total K.E. of mass elements} = \tfrac{1}{2}m \int_0^l v^2 dx$$

$$= \tfrac{1}{2}m \int_0^l p^2\,[a_1 \sin(\pi x/l)]^2\,dx$$

(where p may remain unknown or be given unit value)

$$= \tfrac{1}{2}mp^2a_1{}^2l/2.$$

If equivalent mass is M_1, its K.E. is $\frac{1}{2}M_1p^2a_1{}^2$.
Equating these two values gives $M_1 = ml/2$ as before.

A little thought shows further that the equivalent mass is the same for all the modes of the beam, so long as the reference section is chosen in the middle of a loop; for clearly only the shape of the loops counts, and that is constant in the present case of a uniform beam.

Reverting to mode (*a*) of Fig. 2, it is seen that, having found the equivalent mass M_1 from the shape of the mode, the equivalent spring force K_1 per unit displacement can be found immediately from the frequency p_1, since

$$p_1{}^2 = K_1/M_1 \text{ and therefore } K_1 = p_1{}^2M_1. \quad . \quad . \quad . \quad (14)$$

Every other mode can be represented by an equivalent spring in the same way. In the present case, since M_1 is the same for all modes, the spring stiffness for mode n is

$$K_n = p_n{}^2M_1.$$

An interesting conclusion is that the deflection produced by applying a given load in the middle of a loop varies inversely with the frequency squared, *i.e.* with n^4 (n being the number of loops). The stress for the same deflection at loop centres, however, increases directly with n^2. Thus the stress produced by a given load varies as $1/n^2$, which means that a load applied at the mid-point of the beam produces nine times more stress in mode (*a*) than in mode (*c*) of Fig. 2.

This is one reason why dynamic stress in the higher modes tends to be unimportant.

5. INDEPENDENCE OF THE NORMAL MODES

A main feature of the natural modes is their mutual independence. Consider, for example, the first three natural vibration modes of the uniform beam of Fig. 2. While vibrating freely in any mode it is loaded by inertia forces alone, and their distribution is shown in Fig. 3.

The inertia load distribution is shown each under its corresponding mode. The fact that the beam is uniform in this particular example makes the shape of the load

curve identical with that of the corresponding mode, but that does not affect the argument.

The three load distributions shown are called the first, second and third *Normal Loadings* and the independence of the natural modes lies in the fact that no "normal loading" can produce deflection of the beam in any natural mode other than its own. Thus, the first Normal Loading, if applied under the condition that displacements distributed as in the first mode are denied to it, can produce displacements in no other mode—the beam will remain undeflected. The fact is that the normal loading of one mode does no work when acting over the displacements in another mode.

This is immediately proved in the present example by letting the first Normal Loading act through the displacements in the third mode.

Load at x on element dx in 1st mode varies as $y_1 dx$.

Displacement at x in third mode varies as y_3.

Work done by load element in Mode 1 acting through displacements in Mode 3 varies as $y_1 y_3 dx$

or $$\sin(\pi x/l)\sin(3\pi x/l)\,dx.$$

Total work throughout the beam $= \int_0^l \sin(\pi x/l)\sin(3\pi x/l)\,dx = 0,$

which follows from the fact that

$$\int_0^{\pi} \sin m_1\theta \sin n_1\theta\, d\theta = 0$$

when m_1 and n_1 are whole numbers, and $m_1 \neq n_1$.

Because of this mutual independence the natural modes are said to be mutually orthogonal or normal one to another, hence the term *Normal Modes* used in place of *Natural Modes*. This property of normal modes is their chief characteristic and the main reason for their usefulness.

6. REPRESENTATION OF EXTERNAL LOAD BY A SERIES OF "NORMAL LOADINGS"

It will be seen from the previous remarks that, if the external load could be represented adequately by a number of normal loadings, each such loading would excite only the corresponding mode and would not affect the others. Each, therefore, could be dealt with separately on the basis of the simple equivalent spring.

Actually it *is* possible, remarkable though it may seem, to represent any external load distribution, however arbitrary, by a series of normal loadings if a large enough

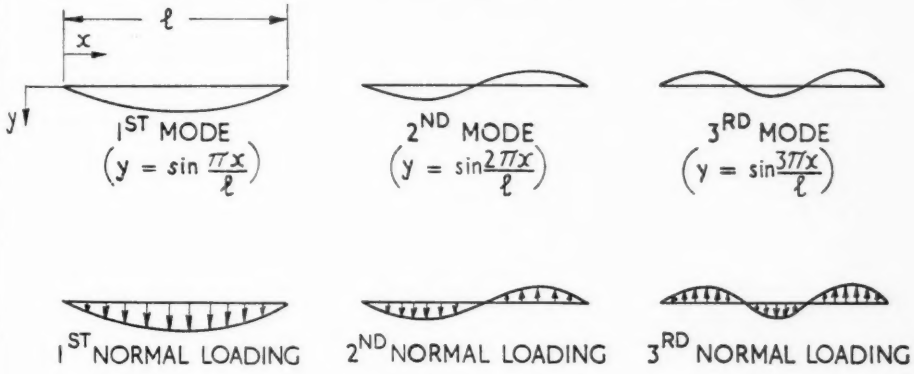


Fig. 3.

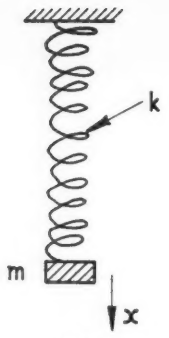


Fig. 4.

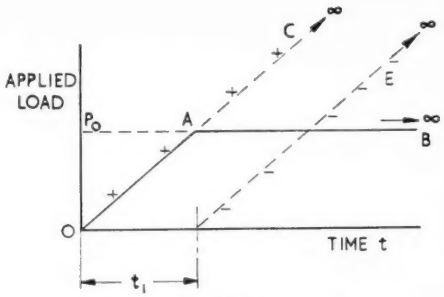


Fig. 5.

number of them is taken. Luckily it is not necessary so to split up the applied load. The mere fact that it is possible enables us to avoid having to do it, as the following argument proves. When the actual external load is being applied, possibly a single concentrated force, it can be imagined as taking the form of the series of normal loadings by which it is possible to represent it. When all those normal loadings are applied to mode (*a*) of Fig. 2, for example, none of them has the slightest effect in producing displacement (and hence stress) except the mode (*a*) component, which shows that it is quite correct to apply the whole external load in each of the modes that is being considered.

Thus, if the response is required of the simply supported beam in mode (*a*) to a constant force P_0 suddenly applied at some section x_1 (and then maintained), it is first transferred to the reference section as the equivalent force

$$P_0' = P_0 \sin(\pi x_1/l). \quad . \quad . \quad . \quad . \quad . \quad . \quad (15)$$

The dynamic displacement in this mode is then obtained from the equation of motion for the equivalent simple spring

$$M_1 d^2y/dt^2 + K_1 y = P_0 \sin(\pi x_1/l), \quad . \quad . \quad . \quad . \quad (16)$$

where y is the displacement at the reference section, and is a measure of the displacement everywhere else. On the face of it, it looks as if every normal loading that is a component of the applied force must be treated in the same way before the resultant displacement obtained by superposing the displacements in the separate modes can be found. Fortunately, this is not the case, for only those component normal loadings that produce an appreciable overswing need be so treated, as will presently appear.

7. EFFECT OF RATE OF LOADING ON THE DYNAMIC OVERSWING OF A SIMPLE ELASTIC SYSTEM

Let the system be that shown in Fig. 4 where

m = mass of suspended weight

k = spring stiffness (force/unit displacement)

x = downward displacement.

Also, let the rate of loading be given by the full line *OAB* of the load-time diagram of Fig. 5, which represents a force growing linearly with time to a value P_0 at time t_1 and thereafter remaining constant. A good way of dealing with such a time-variation of load is to assume the line *OA* produced through *C* indefinitely and superpose another precisely similar load, but of *opposite sign* starting from zero at time t_1. The resultant then gives the curve *OAB*.

It can be shown that up to point A on the load-time curve, the displacement can never be greater than it is at A^*, which means that only times subsequent to t_1 need be considered in seeking the maximum displacement. The equation of motion for OC is

$$md^2x/dt^2 + kx = (P_0/t_1)t \quad . \quad . \quad . \quad . \quad (17)$$

giving

$$x = [P_0/(kt_1)]\ [t - (1/p)\sin pt]. \quad . \quad . \quad . \quad . \quad (18)$$

For DE the equation is

$$md^2x/dt^2 + kx = -(P_0/t_1)(t - t_1) \quad . \quad . \quad . \quad . \quad (19)$$

giving

$$x = -\{P_0/(kt_1)\}\{(t - t_1) - (1/p)\sin p(t - t_1)\} \quad . \quad . \quad . \quad (20)$$

For times subsequent to t_1, the two values of x are superposed to get

$$x = (P_0/k)\,[1 + \{1/(pt_1)\}\{\sin p(t - t_1) - \sin pt\}]. \quad . \quad . \quad (21)$$

The first term is the static deflection corresponding to the load P_0, and the second therefore must represent the added deflection due to the inertia forces. It is seen that the fractional increase of deflection over static deflection

$$(\text{overswing})/(\text{static deflection}) = \left(\frac{1}{pt_1}\right)\{\sin p(t - t_1) - \sin pt\} \quad . \quad (22)$$

which reaches a maximum at time $t = \pi/p + \frac{1}{2}t_1$ when

$$(\text{maximum overswing})/(\text{static deflection}) = \left(\frac{1}{pt_1}\right)\{2\sin(\tfrac{1}{2}pt_1)\} \quad . \quad . \quad (23)$$

Fig. 6 shows this ratio for different rates of build-up of the force in terms of the number of vibration periods necessary to reach maximum load.

It is seen at once that if t_1 is small enough compared with the period $(2\pi/p)$ *i.e.* if the load is applied suddenly enough,

$$(\text{overswing})/(\text{static deflection}) = 1.$$

This agrees with the well known fact that a load applied suddenly produces twice the static deflection. Also, as t_1 becomes large compared with the period $2\pi/p$, the overswing becomes negligible, and the inertia loads need no longer be considered, *i.e.* the problem becomes a static one.

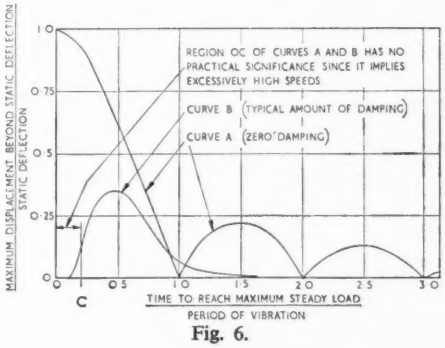


Fig. 6.

It is concluded that, if the lowest natural period of a continuous elastic system is short compared with the time of build-up of the applied forces, the problem of overswing does not arise.

*This follows immediately from the form of equation (18).

8. SEGREGATION OF INERTIA LOADS

In aeronautical structures it often happens that the lowest natural vibration period is not short, when compared with the load build-up time, but the higher vibration periods are. This is as much as to say that the inertia forces are negligible except in the lowest mode, and that, were it not for the inertia loads in that mode, the applied load, no matter what its variation with time, could be regarded as a varying static load and the deflection obtained accordingly.

Clearly, the best course in such a case is first to neglect the inertia loads associated with the lowest mode and to treat the applied load entirely on a static basis, then secondly to evaluate the neglected inertia loads and find the corresponding deflections, in order finally to superimpose the two sets of deflections (or stresses) to obtain the resultant effect. The static part of the problem needs no discussion and the procedure for obtaining the separate inertia displacement may be exemplified by the case of the uniform beam previously discussed for which, for example, the inertia loads in the lowest mode alone (*i.e.* mode (*a*) of Fig. 2) are not negligible.

The external loading may be supposed to be a concentrated load applied at section x_1 varying with time in accordance with the load-time curve of Fig. 5. Transferred to the central reference section, P_0 becomes $P_0 \sin(\pi x_1/l)$ as in equation (15). Knowing the frequency and the equivalent stiffness in the mode concerned (from equation (14)), the resultant displacement may be obtained direct from equation (21) by putting K_1 for k and p_1 for p. Thus

$$x=(P_0/K_1)\,[1+\{1/(p_1t_1)\}\{\sin p_1(t-t_1)-\sin p_1t\}]. \quad . \quad (24)$$

If from this is subtracted the static displacement P_0/K_1, what is left, *i.e.*

$$x_1=\{P_0/(K_1p_1t_1)\}\{\sin p_1(t-t_1)-\sin p_1t\}, \quad . \quad . \quad (25)$$

must be the displacement due to the inertia forces.

The static displacement is at once found from the static bending moment as usual, and on adding x_1 of (25) to this the total displacement is obtained.

9. EFFECT OF DAMPING

The effect of damping in reducing the amount of dynamic overswing in any system dependent on ordinary structural damping is usually small. The overswing for an aeroplane wing, however, suffers a welcome reduction in virtue of the aerodynamic damping, which varies directly with the flight speed. The kind of load-time curve shown in Fig. 5 (to a suitable scale) is generally accepted as the one that an aeroplane wing in a gust must be capable of taking without failure. The time t_1 is that taken by the aircraft to traverse 100 ft. (*i.e.* the distance in which the gust grows to full strength) and varies, therefore, inversely with the flight speed.

It follows from this that the faster the aeroplane travels the more sudden is the gust load, and hence the greater the overswing in the undamped case. With damping an important new factor enters, in that, the faster the speed, the greater the damping. This suggests that there may be a critical speed beyond which the overswing actually falls with increased speed. This point is now investigated, and again in terms of the load-time curve of Fig. 5 and the simple mass-spring system of Fig. 4, which it is known can represent any one of the normal modes of a continuous system such as an aeroplane wing.

Free Vibration with Damping

The equation of motion for a free vibration is

$$md^2x/dt^2+cdx/dt+kx=0 \quad . \quad . \quad . \quad . \quad (26)$$

or

$$d^2x/dt^2+(c/m)\,dx/dt+kx/m=0 \quad . \quad . \quad . \quad . \quad (26a)$$

where the damping term cdx/dt is added, c being the damping force per unit velocity.

The solution gives

$$x = e^{\left[-\frac{c}{2m} \pm \sqrt{\left\{\left(\frac{c}{2m}\right)^2 - \frac{k}{m}\right\}}\right]t} \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

From which it is seen that, if $[c/(2m)]^2 < k/m$, as it always is for air damping, the motion is oscillatory, but when

$$[c/(2m)]^2 = k/m \quad . \quad . \quad . \quad . \quad . \quad . \quad (28)$$

the motion becomes dead-beat, *i.e.* an overswing only just fails to take place; and what settles the effectiveness of a damping force is the nearness with which it approaches dead-beat or *critical damping* as given by (28). Ordinarily the term $[c/(2m)]^2$ is much smaller than k/m so that the quantity under the radical in (27), which determines the frequency, is nearly enough represented by $-k/m$, *i.e.* the value for the undamped case. Then

$$x = e^{\left(-\frac{c}{2m}\right)t}(A \sin pt + B \cos pt) \quad . \quad . \quad . \quad . \quad (29)$$

where A and B are constants depending on the initial displacement and velocity, and

$$p = \sqrt{(k/m)} = \text{circular frequency.}$$

By (28) the critical, or dead-beat, damping is given by

$$c_{\text{crit}} = 2m\sqrt{(k/m)} = 2mp = 2\sqrt{(km)} \quad . \quad . \quad . \quad . \quad (30)$$

and (29) can be written in the form

$$x = e^{\left(-\frac{c}{c_{\text{crit}}}\right)pt}(A \sin pt + B \cos pt) \quad . \quad . \quad . \quad . \quad (31)$$

which shows that the drop in amplitude per period $2\pi/p$, or given fraction of a period, depends only on the ratio

$$\varepsilon = c/c_{\text{crit}} = c/(2mp). \quad . \quad . \quad . \quad . \quad . \quad (32)$$

9.1. Value of ε, *i.e.* c/c_{crit}, for typical large aeroplane

It is shown in Appendix I that for a typical large aeroplane (with wing engines) the value ε is likely to be in the neighbourhood of

$$\varepsilon_0 = 0.36V/(Wp). \quad . \quad . \quad . \quad . \quad . \quad (33)$$

Thus, at sea level, for a wing loading of 57 lb./ft.^{2}, a speed of 400 ft./sec. and a fundamental vibration frequency of just under 3 per sec., *i.e.* $p = 18$ (figures typical of a 150 ft. span aeroplane)

$$\varepsilon_0 = 2.52/p$$
$$= 0.14.$$

The damping therefore is 14 per cent. of critical for this wing loading, plan form and weight distribution.

9.2. Load linear with time up to constant maximum—with damping

Turning now to the typical gust loading of Fig. 5, the device previously used in the undamped case can be repeated, *i.e.* on a load increasing linearly with time to infinity, another of the same kind is superimposed but opposite in sign and starting from time t_1 (when the external load reaches its maximum) as datum. The equation for the first (following equation (26)) is

$$d^2x/dt^2 + (c/m)\,dx/dt + kx/m = P_0 t/(mt_1) \quad . \quad . \quad . \quad (34)$$

from which is obtained

$$x=\frac{P_0 t}{kt_1}+\frac{P_0}{kt_1}\left[\frac{2\alpha}{p^2}\{e^{-\alpha t}\cos\sqrt{(p^2-\alpha^2)}\,t-1\}-\frac{(1-2\alpha^2/p^2)}{\sqrt{(p^2-\alpha^2)}}e^{-\alpha t}\sin\sqrt{(p^2-\alpha^2)}\,t\right] \quad . \quad (35)$$

where $$\alpha=\varepsilon_0 p. \quad . \quad (36)$$

For the numerical values of Section 9.1 α is much less than p, and therefore $(\alpha/p)^2$ is negligible compared to unity.

Thus $$x=\frac{P_0 t}{kt_1}-\frac{P_0}{kpt_1}\left[\frac{2\alpha}{p}(1-e^{-\alpha t}\cos pt)+e^{-\alpha t}\sin pt\right] \quad . \quad (37)$$

On this is superposed the second motion valid only from $t=t_1$,

$$x=-\frac{P_0}{kt_1}(t-t_1)+\frac{P_0}{kpt_1}\left[\frac{2\alpha}{p}\{1-e^{-\alpha(t-t_1)}\cos p(t-t_1)\}+e^{-\alpha(t-t_1)}\sin p(t-t_1)\right] \quad . \quad (38)$$

so obtaining, for $t>t_1$

$$x=\frac{P_0}{k}+\frac{P_0}{k}\frac{1}{pt_1}\left[e^{-\alpha(t-t_1)}\sin p(t-t_1)-e^{-\alpha t}\sin pt+\right.$$
$$\left.+\frac{2\alpha}{p}\{e^{-\alpha t}\cos pt-e^{-\alpha(t-t_1)}\cos p(t-t_1)\}\right] \quad . \quad (39)$$

From this it is seen that the fractional overswing is given by

$$[1/(pt_1)]\ [\text{quantity in square brackets in (39)}]. \quad . \quad (40)$$

In calculating the value of t that makes the overswing a maximum, and in subsequently calculating the overswing itself, it helps matters to remember that, for an aeroplane hitting a gust,

$$t_1=100/V \quad . \quad (41)$$

(the maximum gust force being reached spatially in 100 ft.) so that in equation (33)

$$\varepsilon_0=0.36\times 100/(Wpt_1) \quad . \quad (42)$$

and $$\alpha=\varepsilon_0 p=36/(Wt_1) \quad . \quad (43)$$

$$=0.62/t_1 \quad . \quad (43a)$$

for a wing loading of 57 lb./ft.^{2}, being therefore independent of the frequency p (but, be it noted, dependent on wing loading, plan form and weight distribution).

Thus $$\alpha t_1=36/W$$

$$=\text{constant for these conditions.} \quad . \quad (43b)$$

9.3. Effect of wing frequency on overswing

On examining the expression for the fractional overswing as given by (40) it can be seen that, if the time scale is changed at the same time as the frequency so as to leave the products, pt, pt_1, αt and αt_1 unchanged, the overswing remains the same. This avoids working out the overswing for more than one value of the frequency p, and shows that so long as two aircraft traverse the 100 ft. of gust gradient between zero and maximum in the same fraction of their vibration period, the fractional overswing is independent of the period. This is contingent of course on the wing loading, plan form and weight distribution remaining the same.

Thus, Curve B of Fig. 6, which is drawn on the same time-base as the curve for the undamped overswing, applies to any size of aircraft, and it may be noted that, if the 100 ft. traverse (to reach maximum gust strength) is done in less than half a wing vibration period, the fractional (or percentage) overswing actually falls with

further increase of speed. Thus the suggestion made earlier is borne out and there *is* a critical speed beyond which the increase in damping more than offsets the sharpening of the gust edge in *its effect on the fractional overswing.*

It is important to note that the longer the wing period, *i.e.* in general the bigger the aircraft, the greater the benefit from air damping, because it takes place at a lower speed.

Consider, for example, an aircraft of the size of a Brabazon or Princess. The fundamental frequency is about 1.6 per sec., giving a half-period of 1/3 sec., so that if the 100 ft. gust is traversed in this time the speed is 300 ft./sec. (200 m.p.h.). The fractional overswing is at its peak value of 0.37 beyond static deflection as read from Curve B of Fig. 6. Suppose now such an aircraft to travel at 400 m.p.h. and so traverse the gust in 1/4 of a period. The overswing is now only 0.2 above static but the absolute value of the gust load, since the static force itself goes up directly with the speed, has gone up roughly in the proportion of $2(1+0.37)$ to $4(1+0.2)$ neglecting the fact that the deflections in the static and the overswing case are not quite identically distributed), *i.e.* from 2.74 to 4.8. If, on the other hand, the overswing had not fallen off but increased to (say) 0.6, the gust load at 400 m.p.h. would be $4(1+0.6)=6.4$, or 35 per cent above its actual value.

To put the situation in its proper perspective, it may be said that it is a bad thing at all times for any aircraft to fly fast into a gust, that it is worse for big machines whose slow period accentuates the aircraft speed, but that it is a good thing for such big machines that their slow period brings in its train a welcome alleviation in the form of a reduced overswing. It would be still better if they had a shorter period.

9.4. Segration of inertia-cum-damping forces

If, as in the case of the undamped motion of Section 7, the inertia forces are only appreciable in the lowest mode, the procedure for obtaining the resultant displacement is the same. Thus, the external load, whatever its variation with time, is treated first as a correspondingly varying static force. Next is obtained the separate displacement from the inertia-cum-damping forces for the lowest mode (if only that mode is dynamically excited). This displacement is precisely the overswing discussed in the previous section and is obtained by multiplying the static displacement of the system in *the particular mode* (produced by the whole external load) by the fractional overswing. Thus, the stresses that have to be added to the purely static stresses corresponding to the external load are the stresses due to the displacement produced by the fractional overswing times the external load *in the mode concerned.*

9.5. Coupling effect of damping forces

There is one complicating factor which damping introduces into the dynamic response of a continuous elastic system that is not present when the system is undamped. This is the fact that, since the damping forces in any particular mode, in general, are not distributed in the same way as the normal (or inertia) loading for that mode, they must tend to excite other modes. Conversely the damping forces in the other modes affect the particular mode. Thus a coupling effect is introduced that is not taken account of if each mode is treated independently.

The error introduced by neglecting this coupling is not likely to be appreciable, because a damping force that is directly proportional to velocity, being thereby proportional to amplitude, is correctly distributed if the mass is uniformly distributed, and approaches correct distribution even for a non-uniform distribution of mass.

In many practical cases the difficulty does not even arise because any mode higher than the fundamental produces negligible overswing.

9.6. If higher modes are excited

In certain cases, where for example a concentrated load is applied rather suddenly, the overswing must be considered in modes higher than the fundamental.

The procedure, however, is unaltered. It merely becomes necessary to find the inertia-cum-damping loads (corresponding to the overswing) in the corresponding modes, as well as in the fundamental mode, before adding them together and superimposing them on the purely static deflections. The latter (as indicated in Section 6) automatically and correctly takes full account of all the higher modes that have no overswing.

10. APPENDICES

For ease of presentation a simply-supported uniform beam has been used but a free-free system such as an aeroplane in flight is equally straightforward to deal with, as shown in Appendix III—so long as the appropriate normal modes and their frequencies are known. When direct resonance tests are impracticable, something can be done by calculation, but the best alternative is probably a resonance test on a suitably simplified model of the actual aeroplane.

Appendix I shows how an estimate of the ratio ε can be made with the least resort to particular numerical values. It also discusses the effect of frequency on damping.

Appendix II shows why the dynamic effects are usually important in the fundamental mode alone, while Appendix IV discusses a convenient method for dealing with external loads that are awkward functions of time for analytical treatment.

SUGGESTED COLLATERAL READING

1. Timoshenko, S. (1937) *Vibration Problems in Engineering.* Van Nostrand (1937).

2. Williams, D. and Jones, R. P. N. (1948) Dynamic Loads in Aeroplanes under Given Impulsive Loads. R. & M. 2,221 (1948).

3. Williams, D. (1949) Displacements of a Linear Elastic System Under a Given Transient Load. *The Aeronautical Quarterly*, Vol. I, Part II, August 1949.

APPENDIX I

QUANTITATIVE ESTIMATE OF WING DAMPING IN A GUST

1. INTRODUCTION AND ASSUMPTIONS

It is possible to estimate the value of the air damping of a wing in a gust in terms of the general characteristics of the aeroplane—*i.e.* without having to introduce concrete values for masses, elastic stiffnesses and so on. Such a general approach is adequate for arriving at an approximate figure for the amount of aerodynamic damping, and therefore provides a firm basis for estimating the importance of air damping in reducing the maximum stress induced by gusts.

In considering the behaviour of a typical aeroplane, certain assumptions have to be made about its characteristics, and these may be listed here

(*i*) Wing loading $= W$ lb./ft.^{2}
(*ii*) Flight speed $= V$ ft./sec.
(*iii*) Taper ratio $= 4 : 1$ for the wing plan form
(*iv*) Lift curve slope $dC_L/d\theta = 4.0$*
(*v*) Lowest (fundamental) frequency of the wing in bending $= p$ rad./sec. $= p/(2\pi)$ cycles/sec.
(*vi*) Shape of the fundamental mode of the wing is parabolic (*See* Fig. 7)
(*vii*) The aeroplane carries outboard engines
(*viii*) Weight distribution is as follows when little petrol is carried:

Wing structure and fuel	= 25 per cent.
Fuselage plus contents	= 45 per cent.
Engines	= 30 per cent.

*This assumed numerical value for the slope of the lift curve is the one most open to uncertainty in this estimate of wing aerodynamic damping.

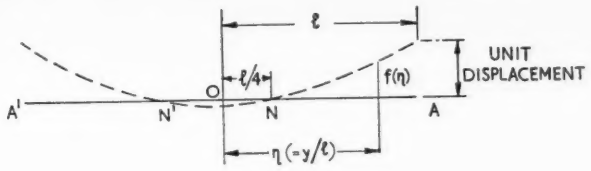


Fig. 7.

Fig. 7 shows the wing in its fundamental mode (shown dotted) displaced relative to the original straight line.

Let y = spanwise distance from the plane of symmetry

l = half span

$\eta = y/l = 1$ at the tip A

$f(\eta)$ = upward displacement in terms of unit tip displacement

$= [(4\eta - 1)/3]^2$

thus giving unit displacement at the tip, zero displacement at the node N, where $\eta = 1/4$, and a negative displacement at the centre O ($\eta = 0$) of amount $1/9$ of the unit tip displacement.

It is assumed that the engines are situated closely enough to the nodes N to produce negligible inertia loads when the wing oscillates in the given mode.

Further, let c_0 = root chord,

and therefore, elsewhere $c' = (c_0/4)\ (4 - 3\eta)$

so as to give the 4 : 1 taper ratio assumed.

2. GENERALISED FORCES

Since the tip displacement x is at all times a measure of the displacement at all other sections, all forces—inertia, elastic and damping—can be referred to that section. This means, for example, that the damping forces actually distributed over the entire wing can be represented, in so far as their effect in producing wing displacement in the particular mode is concerned, by a single damping force at the tip.

The equation of motion can thus be written in terms of the displacement x at the tip. Following equation (26) we have

$$md^2x/dt^2 + cdx/dt + kx = 0 \quad . \quad . \quad . \quad . \quad (44)$$

where m is the effective mass at the tip

c is the damping coefficient per unit tip velocity

k is the elastic coefficient per unit tip deflection.

Thus $$d^2x/dt^2 + (c/m)\,dx/dt + kx/m = 0 \quad . \quad . \quad . \quad . \quad (45)$$

the solution of which is $$x = e^{\left\{-\frac{c}{2m} \pm \sqrt{\left[\left(\frac{c}{2m}\right)^2 - \left(\frac{k}{m}\right)\right]}\right\} t} \quad . \quad . \quad . \quad . \quad (46)$$

Following equation (31) of the main text, this can be written in the form

$$x = e^{-\left(\frac{c}{c_{crit}}\right) pt}\ (A \sin pt + B \cos pt) \quad . \quad . \quad . \quad (47)$$

Thus the damping characteristics can be found if the frequency p and the ratio

$$\varepsilon = c/c_{\text{crit}} = c/(2mp)$$

are known, which makes it necessary to know m as well as p.

3. EQUIVALENT DAMPING FORCE AT TIP (FOR HALF-SPAN)

To obtain c, the effective total damping force at the tip per unit velocity at the tip, each element of damping force at whatever section η it occurs in the span, is transferred to the tip in such a way that its displacement-producing effect is unchanged. In other words the work done by the force element must be unchanged by the transference, so that the force element must be reduced in the ratio of the displacement at η to that at the tip, *i.e.* in the ratio $f(\eta)$ given by the curve of the fundamental mode.

Proceeding thus, and assuming a tip velocity of 1 ft./sec.

$$\text{Velocity at section } \eta = f(\eta)$$

$$\text{Consequent effective change of incidence } \theta = f(\eta)/V$$

$$\text{Consequent change of lift coefficient } = \theta dC_L/d\theta \quad . \quad . \quad . \quad (48)$$

$$= 4f(\eta)/V \quad . \quad . \quad . \quad (49)$$

(if $dC_L/d\theta = 4$).

Change of lift per element of span $ld\eta$

$$= (4f(\eta)/V)\tfrac{1}{2}\rho V^2 (c'ld\eta) \text{ (where } c' = \text{chord)} \quad . \quad . \quad (50)$$

Transferring this to the tip as already described gives

$$\text{Tip element of lift} = 2f^2(\eta)\rho V c'ld\eta \quad . \quad . \quad . \quad . \quad . \quad . \quad (51)$$

Integrating for all the elements in the semi-span gives

$$\text{Tip force} = 2\rho V l c_0 \int_0^1 \{ (c'/c_0) f^2(\eta) \}\, d\eta \quad . \quad . \quad . \quad . \quad (52)$$

or, since $c'/c_0 = (4 - 3\eta)/4$

and $f(\eta) = [(4\eta - 1)/3]^2$,

$$\text{Tip force (for semi-span)} = 2V\rho c_0 l \int_0^1 \left\{ \frac{(4-3\eta)}{4} \left(\frac{4\eta - 1}{3} \right)^4 \right\} d\eta \quad . \quad . \quad (53)$$

$$= 0.1\rho V l c_0 \text{ lb.} \quad . \quad . \quad . \quad . \quad . \quad . \quad (54)$$

(if ρ is in slugs/ft.^{3} of air, V in ft./sec., l and c_0 in ft.).

4. EQUIVALENT MASS AT TIP (FOR HALF-SPAN)

Before the equivalent mass at the tip can be found it is necessary to assume a distribution of mass over the wing itself, as well as the distribution as between wing, fuselage and engines. Starting from the wing loading, W lb./ft.^{2} in level flight, it is seen that

$$\text{Total mass of aeroplane} = (W/g) \times 2l \times (\text{average chord})$$

$$= (W/32) \times 2l \times 5c_0/8$$

$$= 0.04 W c_0 l \text{ slugs.} \quad . \quad . \quad . \quad . \quad (55)$$

Now when an aeroplane strikes a gust the lift from the gust suffers a slight reduction due to the craft moving up with it and, if the aeroplane is stable, a

favourable nose-down pitching. If, however, the gust is sharp—and that is the dangerous type—such alleviation is negligibly small. The absolute value of the gust load therefore tends to be independent of the wing loading. As a fraction of the wing loading the gust load varies inversely with the loading; and so therefore does the normal acceleration. This means that, as the wing loading varies with the amount of petrol carried and the fuselage weight remains sensibly constant, the normal acceleration given to the fuselage by the same gust increases as the petrol is used up. The mass distribution for nearly empty petrol tanks is considered therefore as being the critical case. An average distribution is that already given, *i.e.*

Wing (structure plus fuel) = 25 per cent.
Fuselage plus contents = 45 per cent.
Engines = 30 per cent.

Thus, half-span wing mass, $M_w = 0.125 \times$ (total mass)
$= 0.005 W c_0 l$ slugs,

half fuselage mass, $M_f = 0.225 \times$ (total mass)
$= 0.009 W c_0 l$.

If the reasonable (but arbitrary) assumption is made that the wing mass varies as the square of the chord, assuming m_0 to be the mass per unit length of span at the root,

$$M_w = \int_0^1 m l d\eta = m_0 l \int_0^1 (c'/c_0)^2 d\eta$$

$$= (l m_0/16) \int_0^1 (4 - 3\eta)^2 d\eta = 0.44 l m_0 \quad . \quad . \quad . \quad (56)$$

or $0.44 l m_0 = 0.005 W c_0 l$

and $m_0 = 0.0114 W c_0$. . . . . (57)

To obtain the effective mass at the wing tip, we have, for unit acceleration at the tip,

Mass element at section $\eta = m l d\eta$
Inertia force due to this $= (m l d\eta) f(\eta)$
Equivalent value at tip $= (m l d\eta) f^2(\eta)$
Total for all elements $= l \int_0^1 m f^2(\eta)\, d\eta$

$$= l m_0 \int_0^1 \{ (c'/c_0)^2 f^2(\eta) \}\, d\eta$$

$$= l m_0 \int_0^1 \left\{ \left(\frac{4 - 3\eta}{4}\right)^2 \left(\frac{4\eta - 1}{3}\right)^4 \right\} d\eta$$

$$= 0.02 l m_0$$

$$= 0.02 l (0.0114 W c_0)$$

$$= 0.00023 W c_0 l. \quad . \quad . \quad . \quad . \quad . \quad (58)$$

Equivalent mass of half the fuselage transferred to the tip

$$= M_1 l^2 (\eta)_{(\eta=0)}$$
$$= (0.009 W c_0 l)/81 = 0.0001 W c_0 l.$$

Total equivalent mass at tip (for half-span) $= (0.00023 + 0.0001) W c_0 l$

$$= 0.00033 W c_0 l \text{ slugs} \quad . \quad . \quad (59)$$

so that finally (c being the damping coefficient)

$$\varepsilon = c/c_{\text{crit}} = c/(2mp) = 0.1 \rho V l c_0 / (2 \times 0.00033 p W c_0 l)$$
$$= 0.36 V/(Wp) \quad . \quad . \quad . \quad . \quad . \quad (60)$$

at sea level.

If $V = 200$ ft./sec., $W = 57$ lb./ft.^{2}, $p = 18$ rad./sec. (just under 3 cycles/sec.), corresponding to that of an aeroplane of about 150 ft. span,

$$c/(2mp) = c/c_{\text{crit}} = 0.36 \times 200/(57 \times 18) = 0.07. \quad . \quad . \quad (61)$$

Thus the damping is 7 per cent. of critical damping at a speed of 200 ft./sec. Being directly proportional to the speed, the damping at speed $V = 7 \times V/200 =$ 21 per cent., for example, at $V = 600$ ft./sec., and at $p = 18$.

5. EFFECT OF FREQUENCY ON DAMPING

A point to note is that as the ratio ε is given by

$$\varepsilon = c/(2mp) = c/[2\sqrt{(km)}]$$

and as moreover, *for any given mode*, k is constant, ε varies inversely with m. Thus the effective damping, *i.e.* the ratio c/c_{crit} in the fundamental mode (for example) increases as the weight carried decreases. This increase in damping as the weight carried by the aeroplane is reduced, helps a little to offset the greater "g" loads experienced when the wing loading drops (*See* Section 4 of this Appendix).

A further point of interest is that, as between one mode and another with the same wing loading, the equivalent mass m is much the same (as shown in Section 4 of the main paper) for a low frequency mode as for a high frequency. It follows that the ratio ε tends to vary inversely with the frequency, so that, for example, the effective damping in mode (*c*) of Fig. 2 is nine times less than in the fundamental mode (*a*).

It is fortunate therefore that, as shown in Appendix II, other considerations reduce the importance of the higher modes.

APPENDIX II

WHY THE DYNAMIC EFFECTS ARE USUALLY IMPORTANT IN *THE FUNDAMENTAL* MODE ALONE

There are three main reasons why the dynamic effect, *i.e.* the presence of inertia loads, is only important in the fundamental mode. They are:

(*i*) The higher modes have usually too high a frequency for the external load to have any effect other than a static one.

(*ii*) The static stresses moreover, as already shown in Section 4 of the main paper, rapidly diminish as the order of the mode increases, so that the extra stresses due to inertia loads tend to be a progressively smaller fraction (by (*i*) above) of a rapidly diminishing quantity.

(*iii*) In many cases, of which an aeroplane wing subjected to a gust is a good example, the distribution of the load over the structure is such as to be

unfavourable to the excitation of the higher modes. This is easily seen by considering Fig. 8 which shows the 1st, 2nd, 3rd and 9th mode of the beam discussed in Section 2 of the main paper.

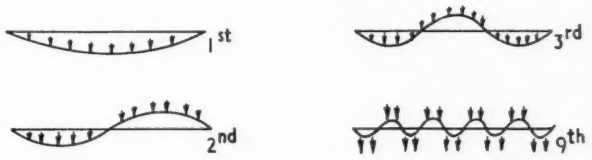


Fig. 8.

It is clear that a force uniformly distributed over the beam can do no work in the 2nd mode (or indeed in any even mode). It can do only a little in mode 3, but next to nothing in the 9th mode since only 1/9 of the load has any chance to do work, the remaining 8/9 being self-cancelling.

A gust produces a well distributed force on a wing and therefore produces stresses that are small, compared with those produced by the same total force applied in a more concentrated form through (say) the undercarriage. In the latter case the inertia loads are likely to be appreciable in a few of the higher, as well as in the fundamental, modes.

APPENDIX III

HOW TO DEAL WITH A FREE-FREE SYSTEM

An elastic system which can only resist a resultant external load and/or couple by virtue of its own inertia is a free-free system. An aeroplane in flight presents such a system, for a gust or a landing impact are both external forces that are only resisted by the inertia of the aeroplane.

A convenient method of approach in such cases is to divide the external load into two systems, which, when added together, give the actual external load. Take, for example, the aeroplane structure indicated in Fig. 9 (*a*), with two wing engines each of mass M_1 and a central fuselage of mass M_0, and let it be subjected to an upward force P at the fuselage.

The first system, "A," is one in which the resultant applied load, *i.e.* P, is spread out over all the masses that together constitute the total mass M of the aeroplane, in such a way that the load on every mass is proportional to that mass. In other words the load P is applied as an upward "gravity" force, so that the load on the fuselage, for example, is PM_0/M and the load on any small mass m is Pm/M. Such a system can produce no stress or deformation of the structure, but merely accelerates it bodily upward. Therefore it can be forgotten.

The second system, "B," consists of the applied load P plus the first system reversed, and is by itself in equilibrium. If P varies with time in any way, the reverse loading "A" varies synchronously. System "B" is capable of deforming the structure and exciting vibrations in the various natural modes of the wing-fuselage system; but it is important to notice that that part of System "B" that is *System "A" reversed cannot excite any mode and that all the work done in deforming the structure is done by the applied load P alone.* Thus, in finding the equivalent external load at the chosen reference section for any particular mode that is being investigated, transference of the actual applied load need alone be considered.

It may be thought that the foregoing statement in italics needs proof. This is simple.

Figure 10 shows the wing-fuselage system deformed into, for example, its fundamental natural mode by loading system "B."

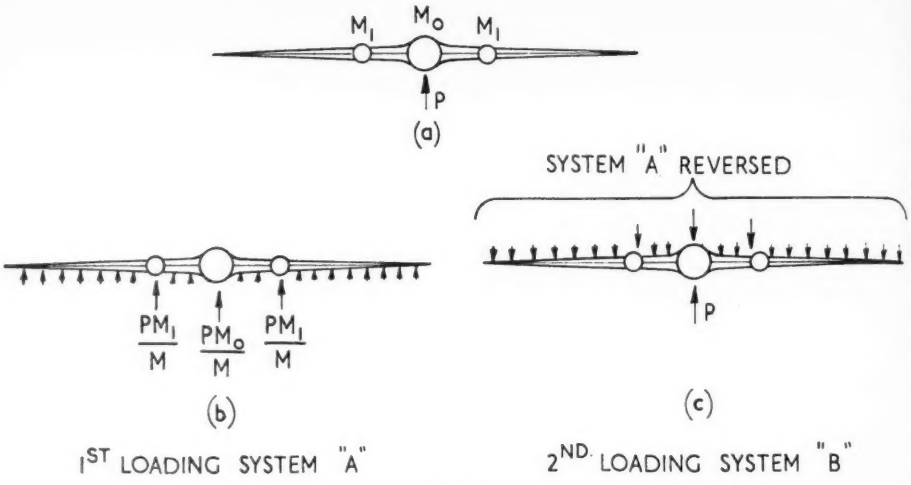


Fig. 9.

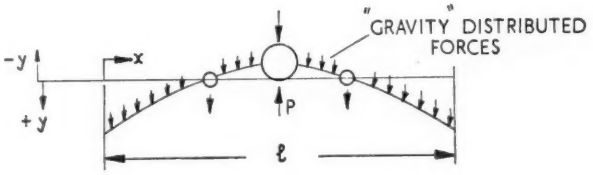
The work done U_A by the gravity type forces of system "A" reversed is

$$U_A = C \sum_{x=0}^{x=l} my,$$

where C is independent of x and varies only with time. Since, however, the structure is displaced in a normal mode it is known that, when vibrating freely at frequency p, the resultant inertia forces must be zero at every moment, or

$$\sum_{x=0}^{x=l} mp^2y = p^2 \sum_{x=0}^{x=l} my = 0,$$

which shows that $U_A = 0$.



(d)

Fig. 10.

APPENDIX IV

METHOD OF TREATING EXTERNAL LOADS THAT ARE AWKWARD FUNCTIONS OF TIME

If the time-variation of the applied force is awkward to deal with analytically, one way of obtaining the displacement is to consider the uniformly varying force as made up of an infinite sequence of elementary impulses. Consider the mass m and spring k of Fig. 4 as being sufficiently representative for present purposes. To generate a sudden velocity v_0 while the displacement is still sensibly zero requires an

impulse of amount mv_0 (the momentum generated). If F is the average force during the very short time δt that the impulse lasts,

$$mv_0/\delta t = F \quad . \quad . \quad . \quad . \quad . \quad (62)$$

or

$$v_0 = F\delta t/m. \quad . \quad . \quad . \quad . \quad . \quad (63)$$

The displacement at any subsequent moment t is

$$x = (v_0/p)\sin pt. \quad . \quad . \quad . \quad . \quad . \quad (64)$$

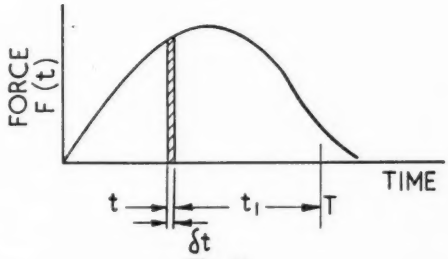


Fig. 11.

A force $F(t)$ varying with time as in Fig. 11 can be regarded as an infinite series of small impulses $F(t)\,\delta t$ of which one is shown occurring at time t. The displacement t_1 seconds later at time T is then from (64)

$$x = (\delta v/p)\sin pt_1, \quad . \quad . \quad . \quad . \quad . \quad . \quad (65)$$

$$= (\delta v/p)\sin p(T-t)$$

$$= \left(\frac{1}{mp}.F(t)\,\delta t\right)\sin p(T-t). \quad . \quad . \quad . \quad . \quad (66)$$

The total displacement at time T due to all the elementary impulses between $t=0$ and $t=T$ is then

$$x = \frac{1}{mp}\int_0^T F(t)\sin p(T-t)\,dt. \quad . \quad . \quad . \quad . \quad (67)$$

Since the system is linear the separate effects can legitimately be added. This integral, if necessary, can be obtained graphically to give x in terms of T. It helps matters to express $\sin p(T-t)$ in the form

$$(\sin pT\cos pt - \cos pT\sin pt)$$

for then, during integration, the quantities $\sin pT$ and $\cos pT$ can be regarded as constants, and a graphical integration is straightforward.

INDICATION, MEASUREMENT AND CONTROL OF ICE ACCRETION

by

Air Commodore D. F. LUCKING, R.A.F. (Ret'd), F.R.Ae.S.

THE RATE of ice accretion on an aircraft depends upon meteorological factors and aircraft characteristics. There are on the one hand atmospheric pressure and temperature; water content; droplet size; electrostatic conditions. On the other hand, there is the collection efficiency made up of aircraft component design characteristics such as size; shape; material; surface finish. Finally, there are aircraft flight variables such as speed; attitude; skin temperature; vibratory state.

Meteorologists are able to define potential icing intensity if they can forecast the ambient factors mentioned. The intensity may be defined as light, moderate, or severe, or by some such broad adjective, with reference to a hypothetical collector. Similarly, the airworthiness authority, *e.g.* the Air Registration Board, must be satisfied that an aircraft can be operated safely in the appropriate meteorological conditions. Therefore the probable association of each meteorological factor with the others needs to be known.

If all of the meteorological factors and all of the characteristics relating to a particular aircraft component are known, it should be possible to calculate what sort of ice will tend to form on the component, and at what rate; also, the heat required per unit superficial area to keep the component free of ice, or, alternatively, to de-ice it periodically. A calculation based on so many variables can hardly be a simple one. For this reason, for checking purposes, and for the economical control of aircraft anti-icing and de-icing means, it is probably desirable to equip aircraft with direct means of measuring icing severity or, in other words, with ice accretion meters.

If an instrument is to measure virtually continuously a real ice accretion rate, and not a potential rate, it must surely include some sort of metering surface(s) on which ice is allowed to accrete, is periodically dispersed, and again allowed to accrete. Such a meter will possess inherent lag, as it will respond to an accumulation of ice over a period. The lag may either be constant and defined by the design of the meter, as in the rotating disc meter[2] seen in the Canadian National Research Council's Rockliffe Ice Wagon, or it may decrease with the icing severity, as in the projected meters described in outline below. The metering surface should have as high a collection efficiency as any part of the aircraft.

It is evidently possible to design an ice detector on an aerodynamic basis. In 1935 a German paper[1] was published suggesting the use of two "static plates," one at each end of a pivoted beam, and only one of them heated, the angular deflection of the beam caused by ice accretion on the unheated end being arranged to operate an electrical indicator.

In 1946 a proposal for a somewhat similar device was put forward by A. Terry, of the Ministry of Supply. This device was based on the equal drag, under non-icing conditions, of a faired and an unfaired body, the bodies being of different sizes to allow for their different drag coefficients. Under icing conditions the built-up ice on the faired body caused its drag to outweigh that of the unfaired body. The resultant torque was measured and related to the atmospheric water content and other conditions.

The Smith Ice Detector also has an aerodynamic basis. In this instrument a pitot leads to a diaphragm chamber having a minute air bleed. When the pitot is closed

Paper received May 1951.

Air Commodore Lucking is Chief Representative of the Ministry of Civil Aviation at the Ministry of Supply.

by ice, the pressure in the chamber falls to static level and causes a switch to close so that the pitot head is heated and a warning light comes on. The ice closure in the pitot is then dispersed and, in continued icing conditions, the cycle is repeated. There seems to be no reason why a device based on the Smith Ice Detector should not be developed to control, through suitable relay means, the automatic anti-icing or de-icing means of aero-engines and aerofoils. A possible disadvantage of the Smith Ice Detector is the sensitivity of small apertures to dust particles and water droplets borne by the air that continuously passes through them.

Some years ago it occurred to the author that an ice accretion meter might be based on the differential behaviour, aerodynamic or otherwise, of two similar bodies, one continuously anti-iced and the other intermittently de-iced. It seemed that such a device might be used as an ice detector, as an ice accretion meter, to control automatically cyclic de-icing, and perhaps to control the heat supply to thermal anti-icing means. The differential behaviour might be manifested by two similar parts of one body, and a cyclic interchange of role between the two bodies, or the two parts of one body, might be valuable for some applications and should not be excluded.

A provisional application for patent (No. 4280/50) was filed in February 1950 outlining a number of applications of the principle already described. An application illustrated in the provisional specification was a pivoted sharp-edged disc, mounted edge-on in an exposed position on an aircraft. A light spring tended to maintain the disc in a defined orientation. The sides of the disc were insulated from each other and each was arranged for electric heating. When the device was switched "on," heat was supplied continuously to, say, the left side of the disc, but only intermittently to the right side. Under icing conditions the additional drag caused by ice accretion on the right side would apply a torque to turn the disc to the right and thus close a switch supplying, through a relay, heating current to the right side, dispersing the ice on it. The disc would then return to its former orientation and the current to the right side be switched off automatically. The disc would thus swing rythmically with a fairly constant overall period. That is to say, under severe icing conditions accretion would be rapid and de-icing slow and, under mild icing conditions, accretion would be slow and de-icing rapid.

The indicating, recording, or servo-control means associated with the metering device in the patent application therefore essentially depended upon the mean rate of heat (or current) supply to the intermittently heated part of the device. For example, servo-controls for electro-thermal cyclic de-icing could be arranged to respond to the varying relation between the accreting and de-icing periods, which relation would depend upon the mean rate of heat supply to the metering device. The disc could be replaced by a rod pivoted at mid-length, or by two hinged and suitably yoked fingers, or by any similar means adapted to electric heating and responsive to differential drag. The possible advantages of a disc are robustness, and that its operation is unlikely to be adversely affected by local irregularities of air flow. It is also expected that only the forward portion of a suitable disc need be exposed.

Instead of air drag some other physical characteristic, such as period of vibration, might be used to indicate unilateral or asymmetric ice accretion between continuously anti-iced and periodically de-iced bodies. In February 1951 the author filed a provisional application for patent (No. 4154/51) for a number of different arrangements wherein the influence of accreted ice on the period of forced vibration of an exposed and intermittently heated reed or wand, produced a pulse of phase interference with the vibration of a similar reed or wand that was screened, or continuously heated, or with the cyclic frequency of an alternator. Such a device could also be used with suitable amplifiers and automatic switches to operate indicating, recording, or servo-control means for anti-icing or de-icing. A device based on differential vibration seems more promising for high speed aircraft than one based on differential drag. It might even prove possible, for meteorological purposes, to instal at a high altitude ground station, or in an aircraft, or radio-sonde balloon, an entirely automatic battery of cyclically-heated vibrating reeds, in pairs of varying collecting efficiences, to record continuously under icing conditions both water content and droplet size. The collection efficiency of a vibrating reed would be difficult to calculate but might be found by calibration, both in virtually still air and at varying wind tunnel speeds.

The use of centrifugal force to amplify the consequence of what may be only a small mass difference is attractive, and another method of using the effect of the differential heating of exposed surfaces to measure ice accretion rates would be to use the mass of accreted ice on the cold side of an asymmetrically heated rotating body to produce an out-of-balance centrifugal force. For example, there might be a miniature windmill having two integral blades free to move in a radial direction, either way, just far enough to operate a micro-switch or influence a magnetic amplifier, but not far enough to produce undue vibration*. One blade would be heated at a time and under icing conditions the integral pair of blades would move radially in the direction of the unheated blade and thus operate switching means for a cyclic interchange of role between the two blades.

It might be possible to incorporate in the boss of the windmill a generator to supply the current to heat the blades and also, to operate extrinsic relays to control thermal anti-icing or de-icing. For research purposes, the collection efficiency of the windmill blades could be varied by design with the intention of making up a set adapted to the measurement, after calibration, of water content and droplet size. Rotating the metering surfaces in this way should help to dispose of melt, for which otherwise special draining arrangements might have to be made, but several considerations would necessarily affect the choice of pitch and r.p.m. for a given air speed. In this method, as in the others suggested, the intention would be to use the heat (or current) consumed to indicate, or record, the rate of ice accretion, or to control anti-icing or de-icing means.

For private reasons, and because there are so many ways of applying the principle advocated, the author has decided to abandon the patent applications, although he confidently hopes that the ideas behind them will prove useful. Indeed, he was recently gratified to learn that the Canadian N.R.C. team, who were informed in August 1950 of the differential drag application, had made a lash-up of it that gave promising results in the icing wind-tunnel. Copies of the provisional specifications may be seen by application to the Royal Aeronautical Society's Librarian.

The N.A.C.A. disc ice accretion meter used in the Rockcliffe Ice Wagon is a remarkable achievement. It automatically records on a chart, by means of a feeler and amplifying devices, the thickness of ice that has accumulated during a part revolution of the disc, to about 1/10,000th inch. The ice film is scraped off behind the feeler, behind which it again starts to build up. The device is possibly less suitable to control thermal anti-icing or de-icing means than some such device as those the author has suggested. One reason for this is that the heat required to disperse ice of a given thickness will depend upon what sort of ice it is, whereas the author advocates the virtually continuous measurement of the heat required to disperse the ice on a metering surface to determine that required for aircraft and aero-engine de-icing, as the most direct and economical of all possible means of automatic and continuous control. On the other hand, ice scrapings are less likely to be troublesome to dispose of than melted ice.

The Rockcliffe Ice Wagon was equipped with a whole battery of ingenious research instruments to measure droplet size and so on, in addition to the rotating disc device. Progress in combating icing has evidently been much greater in Canada and the United States than in Great Britain, mainly because of the greater efforts made, but partly because natural icing conditions are more prevalent.

The author does not wish to comment on the respective advantages of anti-icing[3] and de-icing[4]. They depend necessarily on the conditions, but it is suggested that it would be premature to conclude that it is economically feasible to maintain all vulnerable aircraft surfaces continuously at a temperature giving immunity from ice accretion, even when a lavish source of waste heat is available. It may well prove to be the best solution applicable to turbine engines, but it is already proving difficult to transfer to where it is wanted the amount of heat required to keep wing leading edges and so on continuously above freezing point, when the ambient temperature is far below it, and the installation of combustion heaters in the number of locations required for anti-icing purposes is unwelcome.

Some form of automatic control that adjusts itself to the prevailing conditions is

*It should be easy to restrict the out-of-balance force to that caused by the ice; the blade shift could be compensated.

obviously desirable when cyclic de-icing is installed, and should prove an economy where continuous anti-icing is installed, not only to save fuel and lengthen the life of heat-transfer units, but also to prevent as far as possible the runback that is apt to form aft of the heated area. It may also prove desirable to be able to change in flight the setting of the "gearing" between the automatic control and the anti-icing or de-icing means.

The author has to thank the Ministry of Civil Aviation for permission to publish this note but he alone is responsible for any opinions expressed in it.

References

1. Bottger, R. Suitability of Disc and Cone for Ice Layer Measuring by Aerodynamic Drag. A.A.F. Translation Report No. F-TS-767-RE. 27th August 1946.
2. Jones, A. R. and Lewis, W. A review of Instruments Developed for the Measurement of the Meteorological Factors Conducive to Aircraft Icing. N.A.C.A. Research Memorandum No. A9CO9. 26th April 1949.
3. Beard, M. G. and North, D. Operational Results of Thermal Anti-icing. S.A.E. Preprint for Presentation 9th-13th January 1950.
4. Orr, J. L., Fraser, D., Lynch, J. A. and Rush, C. K. Electro-thermal Methods of Protecting Aircraft against Ice Formation. National Research Council of Canada. 24th July 1950 (restricted).

NEW ZEALAND DIVISION

SECOND ANNUAL REPORT: FOR YEAR ENDED 31st DEC. 1950

DURING the year rules for the government of the four Branches were approved by the Divisional Council, and issued to the Branches. These rules are uniform for the four Branches, subject to minor variations to suit local conditions.

The Council greatly regrets the departure of one of its active members, Professor T. D. J. Leech, who has accepted an appointment in Australia. He has given invaluable service to New Zealand in the field of Science, particularly aeronautics, which has always commanded his enthusiastic and energetic support as Dean of the Faculty of Engineering at Auckland University College during the past ten years. He has been primarily responsible for the encouragement of Aeronautical research in New Zealand.

THE DIVISIONAL COUNCIL 1950

PRESIDENT

Air Vice-Marshal Sir ARTHUR NEVILL, K.B.E., C.B.E., B.Sc., *Associate Fellow* (Wellington)

VICE-PRESIDENT

Professor T. D. J. LEECH, C.B.E., B.Sc., B.E., *Fellow* (Auckland)

COUNCIL MEMBERS

Mr. I. A. SCOTT, *Associate Fellow* (Wellington)
Mr. E. A. GIBSON, O.B.E., A.M.I.C.E., *Associate Fellow* (Wellington)
Wing Commander G. Carter, O.B.E., *Associate Fellow* (Wellington)
Mr. A. W. DINGLE, *Associate Fellow* (Palmerston North)
Mr. H. F. T. ADAMS, M.A., A.M.I.Mech.E., *Associate Fellow* (Christchurch)
Mr. A. H. T. BRAZIER, *Associate Fellow* (Christchurch)
Mr. T. T. N. COLERIDGE, B.E., M.I.Mech.E., *Associate Fellow* (Wellington)
Squadron Leader J. D. ROBINS, D.F.C., *Associate* (Wellington)
Secretary: Mr. T. T. N. COLERIDGE, B.E., M.I.Mech.E., *Associate Fellow* (Wellington)
Assistant Secretary: Squadron Leader J. D. ROBINS, D.F.C., *Associate* (Wellington)
Treasurer: Mr. O. A. KEMP

AUCKLAND BRANCH

Chairman and Council Representative: Professor T. D. J. Leech (*Fellow*).
Honorary Secretary: D. Campbell Allen (*Associate Fellow*).
Committee: B. G. de Bray (*Associate Fellow*), D. A. Patterson, F. A. Reeves, Flt. Lt. J. Stephenson, F. M. Thomas (*Associate Fellow*), A. E. Vause (*Associate*).

Seven general meetings and one visit took place during the year, the average attendance being 40.

The Branch membership is 82 including the Auckland Model Aero Club as a Corporate Member. The Branch held an aeronautics course sponsored by the Council for Adult Education which was well attended. This course included 10 lectures given by members of the staff and honours students of the Auckland University College under the direction of Professor Leech.

PALMERSTON NORTH BRANCH

Chairman and Council Representative: A. W. Dingle (*Associate Fellow*).
Honorary Secretary: F. G. C. Henwood (*Associate*).

Honorary Treasurer: Miss S. Murphy.

Committee: M. R. Roper (*Associate*), Sqdn. Ldr. G. C. Ellis, O.B.E. (*Associate*), A. W. N. Kitto (*Associate*), D. C. Smillie.

During the year Mr. Henwood transferred from the Branch and his duties as Secretary were carried on by Mr. Roper. Mr. E. R. McDonald was co-opted as an additional member of the committee.

The Branch membership is 63. During the year 8 meetings and visits were held, the average attendance being 24.

Canterbury Branch

Chairman and Council Representative: H. F. T. Adams, M.A., A.M.I.Mech.E. (*Associate Fellow*).

Honorary Secretary: A. H. T. Brazier (*Associate Fellow*).

Honorary Treasurer: F. Brooks (*Associate*).

Committee: Professor Rastrick, Sqdn. Ldr. A. Palmer, F. Roper, A. N. Mason, R. Griffiths (transferred to Wellington).

The Branch membership is 31. During the year 10 meetings were held.

Wellington Branch

Chairman: K. H. Day.

Secretary and Corresponding Member: F. J. Steel, D.F.C. (*Associate*).

Treasurer: I. Vigor Brown.

Committee: Group Capt. G. Carter, O.B.E. (*Associate Fellow*), Wing Cdr. R. J. Gibbs, O.B.E., Sqdn. Ldr. J. D. Robins, D.F.C. (*Associate*), J. Gamble.

Five meetings were held during the year, the maximum attendance being 54. The membership of the Branch has increased from 111 to 131.

MEMBERSHIP OF THE DIVISION

During the year the membership of the New Zealand Division has increased considerably. This growth is not completely shown by the membership figures because of an appreciable number of members transferred overseas. The number of members on the New Zealand Register has been as follows:—

1*st January* 1950		1*st January* 1951	
Fellows	2	Fellows	1
Associate Fellows ...	28	Associate Fellows ...	30
Associates	45	Associates	51
Graduates	3	Graduates	5
Companion	1	Companion	1
	79		88

FINANCES

As shown by the Financial Statement, the expenses of the Division have not been great and the financial position is healthy.

LECTURES

The list of papers and lectures given throughout the Branches during the year is as follows. Some of these have been given at more than one branch.

Bird Flight, H. Adams.

The Use of Aircraft Materials in New Zealand, A. Brazier.

Talk and Demonstrations of Material Testing, F. Roper.

Engine Overhaul and Testing in New Zealand, R. Tucker.

Aviation in Other Parts of the World, K. Day (Vacuum Oil Company).

Accident Investigation and Prevention, B. Cornthwaite (Air Department).

Some Current Problems in Development of Gas Turbines, F. F. J. Butler (Civil Aviation Branch).

Symposium, Aerial Top-dressing, Dr. M. M. Burns (Director, Fertiliser Research Association), Flt. Lt. J. Stephenson (Defence Science Corps), A. E. Vause (Aircraft Service Ltd.).

An Introduction to the Aerodynamics of High Speeds, Professor T. D. J. Leech.

Some Economic Aspects of International Civil Aviation, G. N. Roberts (Tasman Empire Airways Ltd.).

Problems in Stressed Skin Structures, D. Campbell Allen (Auckland University College).

Radio and Radar Aids to Navigation, R. J. Dippy (Civil Aviation Branch).

Short Papers: International Airports as related to New Zealand Conditions, D. A. Patterson (N.A.C.) and Impressions of England, Capt. C. J. Le Couteur (T.E.A.L.).

Some Current Problems in Aviation Medicine, Group Capt. P. B. Lee Potter.

Impressions of the S.B.A.C. Show, J. Kerr (de Havilland Aircraft Co.).

In addition a number of films were shown at meetings and there were also a number of general discussions.

Early in the year the Division sponsored a display of aerial top dressing at the Science Exhibition organised in the Town Hall by the Royal Society of New Zealand with allied scientific bodies associated with it. The main theme of this exhibition was science and food and the Division is greatly indebted to volunteers for the work put into preparing this display, largely by members of the staff of the Civil Aviation Branch.

DIVISIONAL COUNCIL 1950-51

G. N. Roberts (Auckland), A. W. Dingle (Palmerston North), H. F. T. Adams (Canterbury), Sir Arthur Nevill, Group Capt. Carter, Sqdn. Leader Robins, T. T. N. Coleridge, E. A. Gibson, I. A. Scott, F. F. J. Butler, A. H. T. Brazier.

ROYAL AERONAUTICAL SOCIETY—NEW ZEALAND DIVISION
STATEMENT OF RECEIPTS AND PAYMENTS FOR PERIOD
1st JANUARY 1950 TO 31st DECEMBER 1950

Receipts	£	s.	d.	*Payments*	£	s.	d.
Balance at 1/1/50				Catering	4	7	6
(*a*) National Bank of New Zealand ...	147	0	8	Envelopes and Stationery	2	1	2
(*b*) Petty Cash ...	1	2	8	Postage Stamps	8	5	6
Subscriptions and Entrance Fees	182	13	6	Telegrams		2	0
				Donation		11	0
				Exchange on Cheques ...		3	0
				Bank Charges		10	0
				Balance at 31/12/50			
				(*a*) National Bank of New Zealand ...	313	16	2
				(*b*) Petty Cash on Hand	1	0	6
	£330	16	10		£330	16	10

I have audited the accounts of the Royal Aeronautical Society (New Zealand Division) and the above is a true and correct statement of receipts and payments recorded. I have not checked the amount of subscriptions due to the Society as a Register of Members was not available.

(Signed) B. W. J. Hoult
B. Com. A.R.A.N.Z.
Honorary Auditor

13*th March* 1951

PRESIDENTIAL ADDRESS

The following address on "Some General Observations of Concern to New Zealand in the Development of Aviation" was given by Air Vice-Marshal Sir Arthur Nevill, K.B.E., C.B.E., B.Sc., A.F.R.Ae.S., following the Annual General Meeting on 13th March 1950.

The annual address before the New Zealand Division of the Royal Aeronautical Society must necessarily be of a general nature. It should preferably be concerned with aeronautics, as distinct from aviation, but in the technical field our progress is distinctly limited and I am forced to deal with the wider field of aviation.

I propose therefore to make some general observations of particular concern to New Zealand in the long-term planning of aviation. This is not a talk on military defence. It is rather a plea for the support of aviation in this country as a matter of long-term national survival. The "Air Power" of the Western World is our chief shield against aggression. In general, scientific and technological superiority is our only answer to the manpower shortage in the Western World.

From the long-term point of view Australia and New Zealand are in an even worse position than other countries of the free democratic world. Mr. Toynbee, a prominent English historian, has referred to "the outlying and precarious footholds of the Western World in South Africa, Australia and New Zealand." A world authority on population, Dr. Warren Thompson, said two years ago that only an Australian population of 30 million and a New Zealand population of 7 million within 25 years would make them safe. This objective is quite unattainable and, I think, over-pessimistic. Bearing in mind the military factors involved, I should feel that a total of 25 million white population in the South Pacific (say 20 million Australia and 5 million New Zealand) should provide a reasonable basis for security, provided that the population is highly advanced in science and technology. This is where the shoe pinches. Compared with other white populations we are primarily food-producing areas and not highly industrialised. We are faced therefore with two problems: an increase in population and a build up of our scientific and technological "know how" to the extent to which we can harness science to our peace-time economy to increase our security. In particular any application of aviation to the solution of these problems, such as the use of New Zealand aircraft to speed up the flow of immigrants, and for aerial works of value to our economy, will greatly increase our readiness for war. Such things, however, require far-seeing and intelligent direction over a period of decades by the Governments of the day and the Departments of State concerned.

In other words, Australia and New Zealand require a common National Air Policy embracing the Air Force, Civil Aviation, Industry and Education. This build-up of air power is a long-term problem of a national character transcending politics and economics. It means the close association of these two countries in the development of aviation, particularly with regard to the aircraft industry and aeronautical research. This policy of Government support in all fields of aviation is amply demonstrated by a study of Air Force budgets overseas, and the type of assistance given to the aircraft industry, to research, operating airlines and the ground organisation involved. The picture is clearly disclosed in the "Report of the President's Air Policy Commission" published over two years ago and on sale to the world for 75 cents a copy. It is entitled "Survival in the Air Age" and is compiled by five prominent civilians with little knowledge and no bias towards aviation. It deserves the closest study by all concerned with defence and aviation.

There is much popular misconception about "Air Power." Many think of it only in connection with the Armed Forces. The enduring features of air power are by no means represented only by the number of combat aircraft in the Air Force. It is of much wider significance to the national life. In this respect it is similar to Naval Power which rests on the seafaring activities of the people, the ship building industry and the mercantile marine. Air Power is similarly a measure of everything that flies and of everything that contributes to all that flies. Its basic elements fall into two general classes. The first of these determines roughly the usable air power

of a nation or a group of nations over a longer period. In the first class are the visible national assets such as, the aeronautical industry; the aeronautical facilities—airports, repair and maintenance, radio, meteorology and air navigation facilities; civil aviation and military aviation.

These are merely evidence of the status of aviation at any one time, and if they are to prove a worthwhile asset in terms of national economy and security, they must be built on sure foundations. The foundations of air power which constitute the air potential of a nation, or a group of nations, rest on deeper considerations; such as geography, natural resources, population, industrial development and Government policy. It is on the correct analysis of these factors—on our strength and weakness in terms of potential air power—that our national Air Policy should rest. I do not propose to examine these considerations any further, except to make the obvious comment "that New Zealand industry is quite unlikely in the future to be self-contained in the field of aircraft manufacture. In this vital element of air power we should support and supplement the Australian aircraft industry."

It is clear from the foregoing that military and civil aviation are basically indivisible, in that they both spring from the same sources. It would be impossible to maintain with any economy or efficiency an Air Force in peace time without civil aviation. Industry, commercial aviation, private flying and the network of ground facilities are all vital to the Air Force. Within certain limits the most practicable, and certainly the most economical, means of increasing potential air power is by the development of every form of productive aviation. In fact, I should go further to say that the extent of the civil aviation activities in peace time is a major factor governing the size of the Air Force, in that recruiting is greatly facilitated if career prospects exist outside the Service.

Let us examine briefly the position in New Zealand today. It must be appreciated that civil aviation has grown out of the war. As a "war asset" it is returning a far greater value than any other. The bulk of the personnel are war trained; the aircraft are still mainly ex-Service transport types, and most of the aerodromes were established to meet Air Force requirements in war. The post-war period of consolidation and development naturally has been most difficult both for the Air Force and civil aviation. Nevertheless, the National Airways Corporation has passed through this period with great credit and small financial loss. Its record compares favourably with that of any other major internal airline. Passenger figures are satisfactorily related to aircraft capacity, although there is considerable scope for expansion when the ground facilities permit economical operation. It is interesting to note in the annual Departmental report, the very high percentage of the public taking air journeys compared with the figures elsewhere. I do not regard air journeys, however, as being a satisfactory index of public favour in a country of such short airline distances as New Zealand. There are today very healthy indications of enterprise and initiative in the field of aerial work. The figures recently quoted by the Minister of 16,000 tons of superphosphates dropped in nine months by 50/70 light aircraft, is a most encouraging approach to a problem of great magnitude and importance to New Zealand and aviation.

A complete survey of the aviation picture shows that we are primarily a "user" country, making a negligible contribution in the field of manufacture and research, and suffering from a serious shortage of scientists and technicians. I doubt if there is any country in the world with more aviation per capita and less technical background. This might be acceptable in a world of free trade private enterprise and absolute security, but it is unsafe today. Even ignoring these factors, the extent and variety of aviation in New Zealand calls for a small research and development organisation. Apart from motives of self-interest, we have undertaken, as part of a Commonwealth plan, to contribute to aeronautical research, which is an added reason for some effort in this field.

Similarly, with manufacture there should be more capacity to help ourselves, at least with regard to assembly and modification of airframes and associated equipment, especially electronic equipment. The future should see a steady build up in

self-sufficiency of Australia and New Zealand in this field. It is a matter of Government policy in Australia which is being energetically pursued.

The Western World is facing an acute shortage of scientifically trained manpower. Science is presenting us with equipment which we do not know how to use. I doubt whether our educationalists have caught up with the needs of this technological age. Many of you have no doubt examined the Report prepared in 1949 on the Education, Training and Supply of Professional Engineers in New Zealand. I would regard it as conservative in the light of the pressing needs facing us today. But it is an excellent report which should be implemented as rapidly as possible.

Aviation is so commonplace that most people overlook the over-riding part played by the Government. The airline operator and the private flyer are merely the end product of Government policy. The national network of airports, navigation aids, communication facilities, and meteorology, must necessarily be provided and controlled by Government, preferably through a single Department of State. These are essentially matters for long-term planning. In building up a key plan in this small country, I would most strongly urge vision in the matter of airports. Unless we look 50 years ahead we are bound to be increasingly embarrassed. In this connection, I suggest that the most important factor is the proximity of airports to the centres which they serve, or will serve. New Zealand is a country of short airline distances, from which follow two important considerations. In the first place, the benefits of aviation will never be realised if the public have to spend twice as long on the ground as in the air. Secondly, traffic densities must be much heavier, which means that route and terminal congestion is bound to become a serious problem demanding every possible scientific aid to ensure safety, reliability and maximum utilization of airports.

I wish to make a final remark about aerial top-dressing and farmer services in general. I am sure there is a great task to be done in this country. The very reasonable prospect in this hungry and envious world of greatly increasing our productivity, which establishes our moral right to stay here, and which increases the population we can carry without sacrificing our standards, and not least of all, increases our security—these things should surely justify universal support. The task again requires extensive planning if it is to be carried out on a worthwhile scale. It calls in the initial stages for heavy capital expenditure and the use of both heavy and light aircraft. There are plenty of difficulties and I am sure that they will all be pointed out, but the prize is a glittering one to those who value the future welfare of this country.

To summarise briefly: we know that military aviation is essential to our security. We must recognise that it cannot be maintained except on a purely artificial, insecure and expensive basis without a virile civil aviation. The latter can make a great contribution to our national economy in peace time.

Our consistent policy should be to encourage the application of aviation to our economy, employing our own nationals and aircraft, and at the same time, developing in conjunction with Australia the necessary degree of self-sufficiency to carry us through the breakers ahead.

REVIEWS

FOUNDATIONS OF AERODYNAMICS. A. M. Kuethe and J. D. Schetzer. John Wiley & Sons Inc., New York. Chapman & Hall Ltd., London. 1950. 374 pp. Illustrated. Index. $5.50, 46s. net.

Such great strides have been made in the last decade in the fundamentals of aerodynamics—mainly concerning the flow of compressible fluids—that a good text-book covering the whole field will be welcomed. Messrs. Kuethe and Schetzer, Professor and Associate Professor respectively, at the University of Michigan, have written such a book and it fulfils its purpose admirably.

The book is divided into three, almost equal, parts devoted to the flow of (*i*) the perfect fluid; that is, one that is incompressible and inviscid, (*ii*) a compressible but inviscid fluid, and (*iii*) a viscous but incompressible fluid. The authors make clear the limitations of the classical aerodynamics derived from considerations of the perfect fluid and show that, by abandoning the assumptions one by one, the flow characteristics at high Mach number and those in boundary layers and wakes can separately be predicted. A chapter is added on the interaction of viscous and compressibility effects, and a final chapter sums up wing characteristics and the effect on them of Mach and Reynolds numbers.

Although no previous knowledge of aerodynamics is required of the reader, a graduate standard of physics and of mathematics is assumed. In spite of the mathematical approach the authors are at pains to explain the physical significance of every result obtained and have been very successful in doing so. Whenever an example is needed to illustrate the argument one has been inserted in the text, and some hundred more are added at the end of the book. The text has been used in America as the basis of a one year post-graduate course for specialists in engineering, mathematics or physics.

There are many in this country now who are taking up aeronautical work without having had a grounding in the foundations of aerodynamics. For them this book gives an admirable introduction to the complex and specialised problems facing us today. There are also many aerodynamicists who have become specialists in one branch of their subject and who have been unable to keep abreast of developments in other branches. For them, too, this review of the fundamentals will be found stimulating.

It is pleasing to find that the authors are not unaware of the many fundamental contributions made to aerodynamic theory by the British. References to original work are given in footnotes and include many to British papers and at least one to an A.R.C. report not generally available over here. The terminology and notation are very similar to those used in this country except that temperatures are quoted in "degrees Rankine" (that is, Fahrenheit Absolute). We can hardly claim consistency on this side of the Atlantic since we use "degrees Kelvin" in most of our scientific work while allowing the meteorologists and doctors to use "degrees Fahrenheit." Nevertheless "degrees Rankine" will be unfamiliar to many and it is a relief to find that the equations involve mainly the "relative absolute temperature" which is the same in any language.

The book sums up the fundamentals of aerodynamics of the homogeneous fluids in which we now fly. The authors warn us, however, that at great altitudes the assumption of homogeneity is not justified, but at present do not go beyond giving a table of the properties of the atmosphere up to 250,000 ft.

AIR SYSTEMS FOR AIRCRAFT. C. A. H. Pollitt. Pitmans. London. 1950. 176 pp. 93 illustrations. Index. 25s. net.

It is unfortunate that the fly-sheet describes this book as up-to-date and suggests that it will be of considerable value to students of aircraft design. Many of the units described have been obsolete for ten years or more and current practice is barely hinted at. The one redeeming feature of the book is that the author gratefully acknowledges the assistance of a number of firms, without whose aid the book could not have been written. It appears that none of the illustrations and little of the

subject matter is original, large parts being taken from catalogues, brochures and Air Publications.

The book is divided into sections dealing with the systems and units of various manufacturers and there is no critical appraisal of the systems described. The text is more suited to a maintenance manual than to a serious work on an important subject, a mass of descriptive detail tending to obscure the main issues. For example, a spring washer under a screw is mentioned but there is no reference to pipes, nor any hint as to how their sizes are mentioned. Vital components such as sealing devices and valve seats are not described and there is not even a circuit diagram for a typical aircraft pneumatic system. This tendency characterises the book and greatly detracts from its value.

Chapters are devoted to pneumatic gun firing equipment and the B.T.H.—Hertzmark Compressor; these are of historical interest. Low pressure rotary air pumps are mentioned but apart from a brief reference in the introduction there is no indication of their use. A section is devoted to air conditioning and cabin heating systems. This subject alone would merit a full-length book and the treatment here is necessarily sketchy. It is based largely on American practice. In this, as in other sections, the student will search in vain for guidance as to which system to adopt and when. The last chapter, however, does give some data on the characteristics of metal bellows which may be of use to a designer, but here again the source is American and the applicability is limited.

The standard of printing, paper and illustrations is good but this alone does not justify the price. The reader has a right to expect an answer to the question, "Why pneumatics?" This book says much but leaves most unsaid and the Industry awaits an authoritative work on the subject of aircraft pneumatics, or at least an accurate and comprehensive guide to modern practice.

NEWNES ENGINEER'S REFERENCE BOOK. Edited by F. J. Camm. George Newnes Ltd. London. 1951. (Fourth Edition.) 1,727 pp. Illustrations. Index. 50s. net.

A fourth edition of this well known reference book, first published in 1946, is now available. Some 120 pages of new material have been added at the end of the book, but otherwise there are few changes from the previous edition. The volume has not quite reached the "over 1,800 pages" claimed on the dust cover. Even so, with over 1,700 it is quite a massive work and no doubt Mr. Camm's main problem has been to keep it within manageable proportions. Data appertaining to mechanical engineering are almost without limit, so there must be an embarrassingly large number of items competing for inclusion.

The whole volume bears evidence of much care and thought in its compilation, and it is no mean achievement to bring so much useful information under one cover. The book begins with summaries of elementary physics, mechanics and mathematics, concluding with the usual tables. Then follows a chapter on drawing office practice based largely on British Standard Specification 308. The next chapter, "Patent Designs and Trade Marks," seems rather out of its place, as does the following, "Machine Knobs and Handles."

After a few formulæ for the bending stresses in simple beams, the book goes on to deal with the commoner mechanical engineering elements—plain, ball and roller bearings, springs, couplings, keys and keyways, toothed gearing and screwed threads. Principles, applications, manufacture and inspection are described in a clear manner and numerous tables give all relevant information on standard ranges. Nearly 200 pages are given to the subject of screw threads alone, the section on the gauging and measuring of these being particularly informative and interesting.

The next part of the book describes the usual machine tools—lathes, drilling, planing, shaping, milling machines, presses, sheet metal manipulating machines, etc. In these days of limited shops experience both as regards time and variety, these chapters contribute much to an appreciation of manufacturing methods and the scope of the various equipment.

A hundred pages on metals and their production and finishing, provides the novice with a useful introduction to the science of metallurgy. There is also a chapter on plastics, a material which is finding increasing application in the industrial sphere.

Further sections deal with factory services, production control, works cost accounting and the like. The chapter on quality control, though primarily a matter for Inspection, is of obvious interest to all design personnel.

The new sections already mentioned mainly consist of tables and call for little comment.

This book, which is clearly printed and well bound, should be studied by aircraft design personnel, including the specialist whose narrow field too often causes him to lose sight of more practical issues.

ALUMINIUM AND ALUMINIUM ALLOY SECTIONS. British Standards Specification. B.S.1161 : 1951. 5s. net.

This recent publication of the British Standards Institution contains tables of areas, centres of gravity, moments of inertia, radii of gyration, moduli of sections and weights of equal and unequal angle sections over a large range of sizes. Similar information is also given for channel, I and Tee sections.

B.S.1161 is a revision of a standard first published in 1944, and it has now been extended to cover additional sizes of aluminium alloy sections and to include sections made for incorporation in designs.

The sections covered are as follows:—

Equal angle	$\frac{3}{4}$ in. × $\frac{3}{4}$ in. to 9 in. × 9 in.
Unequal angle	$1\frac{1}{2}$ in. × 1 in. to 12 in. × 6 in.
Channel	3 in. × $1\frac{1}{2}$ in. to 12 in. × 4 in.
I	3 in. × $1\frac{1}{2}$ in. to 12 in. × 6 in.
Tee	1 in. × 1 in. to 9 in. × 9 in.

CORRESPONDENCE

CLEAR AIR TURBULENCE

In his reply to the discussion on his paper, "Clear Air Turbulence over Europe" (JOURNAL April 1951), Dr. Hislop said (p. 224) that the evidence of an upper air observation at Downham Market in East Anglia need not necessarily apply to Heligoland, 300 miles distant. This is certainly true. Upper air observations were available from North West Germany, however, as is stated in the paper quoted by Dr. Hislop as his reference No. 13. The wind observations made with British equipment at Jever (35-40 miles from Heligoland) and Schleswig (70 miles from Heligoland) and within $\frac{3}{4}$ hour of the reported turbulence incident (Flight VR 27), showed conclusively that shear in the vertical, measured over a depth of a few thousand feet, was small; in fact the wind above Heligoland between 30,000 and 40,000 ft. was probably less than 15 knots at the time of the B.E.A. flight.

J. K. Bannon

Quoting from "The Sun, the Stars and the Universe" (Dr. W. M. Smart, M.A., Professor of Astronomy, Glasgow), it is apparent that periodically the earth in its orbit encounters meteor swarms. There are several meteor swarms, one of which, for example, the "Leonid" shower has a period of 33 years, occurring 14th November.

It is estimated that during maximum intensity the earth nets meteors at the rate of *75,000 per hour*. The majority burn up in transit through the atmosphere.

Those that get through will be of fair mass.

A rough estimate gives meteor speeds up to *25 miles per second*.

May I suggest a relationship with the clear air turbulence investigated by Dr. G. S. Hislop (JOURNAL April 1951).

Thomas David, *Associate*

an appreciation

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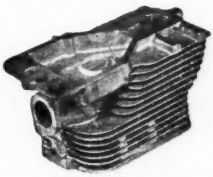

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It is regretted that because of the increasing costs of production it has been found necessary to increase the price of the Journal. From January 1951 (Volume 55, Number 481) the price of a single copy has been increased to 10s. (10s. 3d. including postage), and annual subscriptions to £6 3s. 0d., including postage.

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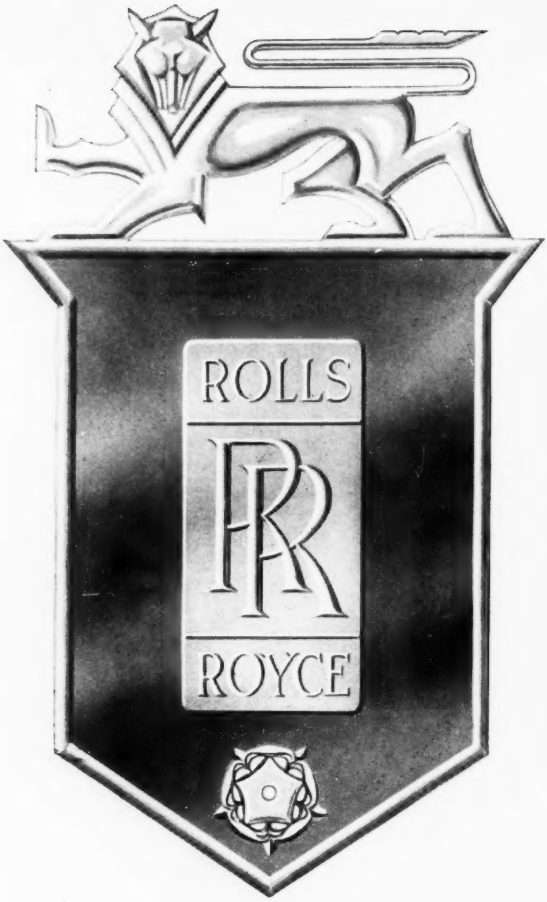

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